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Seismic Measurement of Concrete Strength Properties

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Final report

Prepared for Headquarters, Air Force Civil Engineer Support Agency
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Abstract: An assessment of the portable seismic pavement analyzer (PSPA) was conducted during the period February to April 2005 on three military airfields in order to determine the feasibility of rapidly obtaining the modulus and flexural strength of portland cement concrete and asphalt concrete pavements. The PSPA is a nondestructive testing device that measures seismic modulus using ultrasonic surface waves. The objective of this research is to evaluate the PSPA as an alternative to core sampling. This would potentially reduce the amount of time required for testing and eliminate the need for laboratory testing of concrete cores. This report provides (a) background information on the PSPA, (b) a summary of recent PSPA research, (c) test methods used in airfield evaluations, (d) field testing information, (e) data analysis, and (f) recommendations for utilizing flexural strength relationships.

Contents

Figures and Tables

Figures

Tables

Preface

The project described in this report was sponsored by Headquarters, Air Force Civil Engineer Support Agency, Tyndall Air Force Base, Florida.

This publication was prepared by personnel of the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. The findings and recommendations presented in this report are based upon a series of field tests conducted at Hurlburt Air Force Base in Fort Walton Beach, FL, Barksdale Air Force Base in Shreveport, LA, and Phillips Army Airfield in Aberdeen Proving Ground, MD, in January, February, and April 2005, respectively. The research team consisted of Haley P. Bell and Terry V. Jobe, Airfields and Pavements Branch (APB), GSL. Bell prepared this publication under the supervision of Don R. Alexander, Chief, APB; Dr. Albert J. Bush III, Chief, Engineering Systems and Materials Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

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Unit Conversion Factors

Non-SI units of measure used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
kips (force) per square inch	6.894757	megapascals
pounds (force) per square inch	6.894757	kilopascals

Summary

The U.S. Army Engineer Research and Development Center, Vicksburg, MS, conducted an evaluation of the portable seismic pavement analyzer (PSPA) to determine the feasibility of rapidly obtaining the modulus and flexural strength of portland cement concrete (PCC) and asphalt concrete (AC) pavements. PSPA test results from Hurlburt Air Force Base, Fort Walton Beach, FL, Barksdale Air Force Base, Shreveport, LA, and Phillips Army Airfield, Aberdeen Proving Ground, MD, were combined with data from other recent studies to evaluate the test equipment and develop correlations with PCC properties.

Results of the PSPA evaluation led to the following conclusions:

a. The PSPA provides a reliable measure of PCC modulus.
b. A correlation between the PSPA modulus and flexural strength was developed based on data from the 1996 Pavement Technical Assistance Program and 2005 Innovative Pavement Research Foundation studies:

$$\textit{flexural strength} = 0.12 * E_{PSPA}$$
$$R^2 = 0.53$$

c. The average flexural strength obtained from the PSPA modulus correlation is closer to the actual average flexural strength determined from the beam tests in the laboratory than the flexural strength from the tensile splitting correlation.
d. The flexural strength obtained from the PSPA measurements is consistently around 20% less than comparable flexural strength obtained from tensile splitting tests.
e. The battery life of the PSPA is approximately 3 to 5 testing days, and should be replaced routinely.
f. The rubber pads on the feet of the PSPA show wear and tear after about 1 or 2 days of testing and should be checked and replaced routinely.
g. The PSPA will not provide valid measurements on severely cracked pavements.
h. Thickness estimates from the PSPA are not accurate enough for evaluating pavement; however, additional research could potentially yield the desired accuracy.

Based upon the information presented in this report, the following recommendations are given for using the PSPA on AC and PCC airfield pavements:

a. Use the following correlation when relating the PSPA modulus to flexural strength:

$$\textit{flexural strength} = 0.12 * E_{PSPA}$$

b. Replace the batteries after approximately 3 to 5 full days of field testing.
c. Inspect the rubber pads on the feet of the PSPA after every day of testing.
d. Remove and replace the rubber pads on the bottom of the source and the receivers when they begin to show wear and tear, generally every 1 to 2 days.
e. Test the PSPA at least four times in a feature with three test repetitions at each location for a 95% confidence level.

Chapter 1 of this report presents the objective and scope of the project, and Chapter 2 discusses background information relative to the PSPA. Chapter 3 summarizes the Headquarters, Air Force Civil Engineer Support Agency, airfield pavement evaluation procedures and past studies related to the PSPA. Chapter 4 discusses the field testing methods, and Chapter 5 summarizes the results and findings from the PSPA airfield assessments. Chapter 6 provides the conclusions and recommendations of this investigation.

1 Introduction

General

The Air Force Civil Engineer Support Agency (AFCESA) airfield pavement evaluation teams are under constant pressure to provide accurate field assessments of pavement load-carrying capacity. Pavement evaluation results provide critical information needed by MAJCOM engineers for mission planning and optimization of rehabilitation strategies. Often, the AFCESA airfield pavement evaluation teams remove 100 to 150 core samples per airfield evaluation. The AFCESA has an immediate need for nondestructive testing equipment and analytical procedures for assessing the integrity of portland cement concrete (PCC) and asphalt concrete (AC) pavements onsite, thus virtually eliminating the cost and time delays associated with obtaining concrete cores and awaiting laboratory test results. Seismic testing techniques have shown great promise, and recent equipment developments make this a potentially viable option.

The portable seismic pavement analyzer (PSPA) was developed by Geomedia Research and Development, El Paso, TX, for the Federal Highway Administration's Strategic Highway Research Program to detect problems with pavements in early stages. Additional research and development has been conducted under a U.S. Army Small Business Innovative Research program. The PSPA (Figure 1) is a simple, nondestructive device that rapidly measures Young's modulus via ultrasonic surface waves, completing tests within a few seconds. The purpose of the PSPA is to estimate the in situ seismic modulus of concrete pavements and determine relevant strength parameters for use in pavement evaluations.

Objective

Removal of concrete cores allows for visual inspection of the entire surface layer, accurate thickness measurements, and provides a cylindrical specimen for laboratory tensile splitting testing. However, obtaining concrete core samples is costly, destructive, time-consuming, and may not be representative of the pavement feature. With nondestructive testing methods, there is minimal interference with airfield operations. The objective of this research is to evaluate the PSPA as an alternative to core sampling. This would potentially reduce the amount of time required for testing and

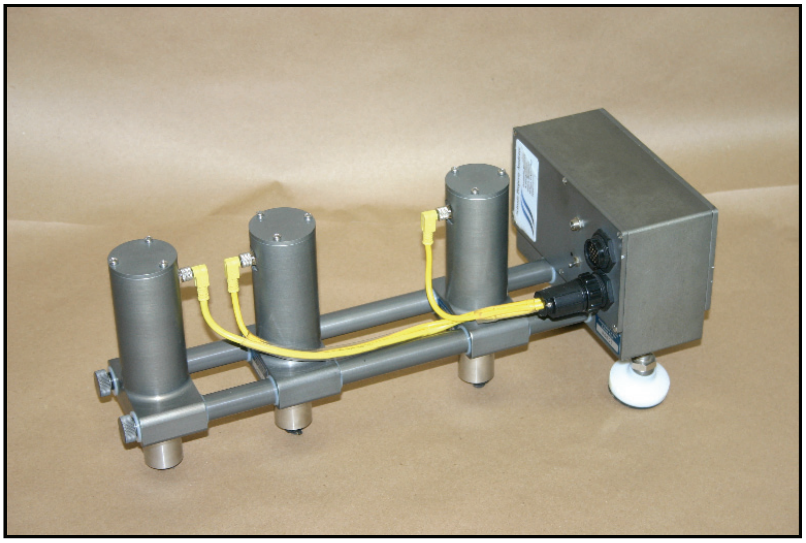

Figure 1. Portable seismic pavement analyzer (PSPA).

eliminate the need for laboratory testing of concrete cores. This report provides data for the following:

a. Evaluating the reliability and ruggedness of the PSPA under field test conditions.
b. Compiling available PSPA studies and developing procedures for incorporating seismic testing into existing structural pavement evaluation methods.
c. Developing correlations between seismic measurements and concrete material properties.
d. Statistically assessing the variability of PSPA measurements and estimating the sampling requirements to ensure reliable results.

Scope

PSPA tests were conducted on the in situ pavements near core hole and falling weight deflectometer (FWD) test locations at Hurlburt Air Force Base (HAFB), Fort Walton Beach, FL, Barksdale Air Force Base (BAFB), Shreveport, LA, and Phillips Army Airfield (PAAF), Aberdeen Proving Ground, MD. Free-free resonant column (FFRC) tests were conducted on the core specimens. These data were analyzed to identify trends in concrete material properties and measured PSPA values. This report provides background information on the PSPA, a summary of recent PSPA research, test methods, field testing, data analysis, and recommendations for obtaining flexural strength relationships.

2 Background

Description of the PSPA

The PSPA is controlled by a laptop computer, which is connected to an electronics box, through a cable that transmits power to the receivers and the source. The source impacts the pavement surface, generating waves that are detected by the receivers. The measured signals are returned to the data acquisition board in the computer. The velocity at which the waves propagate is determined, and the modulus is computed. The PSPA measures the upper portion of the surface pavement layer (Yuan et al. 2005). Figure 2 shows the components of the PSPA.

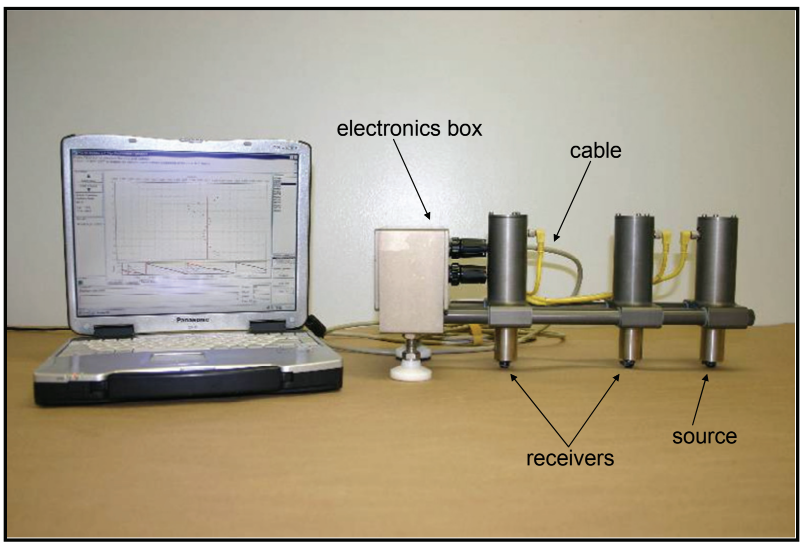

Figure 2. Laptop computer and PSPA components.

The source generates about five or six taps when the PSPA is operating. The first two or three taps are used to automatically set up the amplifiers, and the last three are used in the data collection and analysis.

PSPA parameters

Below is a list of parameters the PSPA uses when determining the velocity and estimating the seismic modulus. The actual values of the parameters vary based on the type of pavement, the condition of the pavement, and the temperature of the pavement.

Mass density, ρ
Poisson's ratio, ν
Rayleigh wave velocity, V_R
Compression wave velocity, V_P

Poisson's ratio is the ratio between transverse strain and longitudinal strain. Rayleigh waves are surface waves that have longitudinal and transverse motion, while compression or primary waves are compressional waves that have only longitudinal motion. The values for mass density and Poisson's ratio are directly incorporated in the calculations used to compute modulus. These values are preset to determine the amount of data required to adequately characterize the modulus using the PSPA.

Seismic testing

The SpaManager is the software that is used to acquire and analyze data from the PSPA. Two types of seismic data generated by the PSPA are used in the SpaManager software: ultrasonic surface waves (USW) and impact-echo (IE). USW are used to estimate the pavement stiffness, and IE is used to estimate pavement thickness. The combination of these techniques offers a powerful analytical capability.

USW measure the modulus of the top pavement layer by adjusting the sensor spacing and frequency range of the PSPA. This method works by measuring the velocity of the surface seismic waves generated by the tapping of the energy source. These waves propagate through the surface material to the two receivers, which is used to determine the properties of the surface layer (Yuan et al. 2005).

The IE method is based on stress or sound waves that propagate through the concrete pavement slab. The waves reflect off the bottom and top of the surface layer, and the frequency of the reflected waves is sensed by the receivers at periodic time intervals (Sansalone and Streett 1998). Surface pavement thickness is then estimated based on the travel time of the waves (Yuan et al. 2005). Currently, the use of the IE method with the PSPA to determine pavement thickness for airfield evaluations has not been validated.

PSPA calculations

A number of steps are required in order for the PSPA to estimate Young's modulus. The calculation shown below is performed internally to make the PSPA more user friendly. The distance between the two receivers is known, and the PSPA measures the travel time of the waves from the source to the receivers. With a known velocity, the modulus can be calculated using Equation 1. Mass density and Poisson's ratio are estimated values based on the pavement conditions selected in the SpaManager software.

$$E_{PSPA} = 2\rho\left[(1.13 - 0.16\nu)V_R\right]^2(1+\nu) \tag{1}$$

where

E_{PSPA} = measured PSPA modulus
ρ = mass density
ν = Poisson's ratio
V_R = Rayleigh wave velocity

A design modulus must be utilized when the PSPA is used to evaluate AC pavements. The AC design modulus (see Equation 2) corrects the estimated modulus to a temperature of 77 °F (25 °C) and a design frequency of 15 Hz using the following equation (Nazarian et al. 2005).

$$E_{77^oF} = \frac{E_{PSPA}}{\left(\left\{-0.0109 * \left[(T-32) * \frac{5}{9}\right] + 1.2627\right\} * (3.2)\right)} \tag{2}$$

where

E_{77^oF} = design modulus of the AC pavement
T = AC pavement temperature

The conversion from measured modulus to design modulus is not performed automatically by the PSPA. It must be incorporated during postprocessing when analyzing the AC pavements data.

Free-free resonant column test

The FFRC test measures the seismic modulus of concrete directly from the core samples. An accelerometer, connected to a signal conditioning unit, is securely placed on one end of the cored sample, while the other end of the accelerometer is connected to a laptop computer. A hammer is used to generate an impulse load to the free end of the core, and the accelerometer measures the resonant frequencies transmitted through the specimen. Once the resonant frequencies and dimensions of the cored sample are known, the modulus is determined using the principles of wave propagation in a solid rod (Yuan et al. 2005).

The FFRC test was used in this evaluation because it provides direct seismic measurements on core samples that can be compared with the seismic measurements of the PSPA. The PSPA generally measures the modulus from the upper portion of the pavement; therefore, 10% must be added to the PSPA modulus of the same sample tested in order to compare it directly with the FFRC modulus. The modulus measured by the FFRC test can be found by using Equation 3 (Yuan et al. 2005).

$$E_{FFRC} = \rho(2 f_L L)^2 \tag{3}$$

where

E_{FFRC} = measured FFRC modulus
f_L = longitudinal resonant frequency
L = length of the core sample

3 AFCESA Airfield Evaluation Procedures and Related Studies

AFCESA airfield evaluation procedures

For an airfield evaluation, the AFCESA airfield pavement evaluation team normally has one person operating the falling weight deflectometer and another small team taking core samples. Generally, the AFCESA airfield pavement evaluation team obtains approximately 100 to 150 cores per airfield evaluation. Dynamic cone penetrometer tests are also conducted at the core hole locations to determine the strength of the underlying soil layers. At the end of each day, the ends of the cores are sawn, and tensile splitting tests are performed onsite. From the tensile splitting tests, the maximum applied load is determined, and the tensile splitting strength is calculated using Equation 4, which is derived from the theory of elasticity.

$$\sigma = \left[\frac{2 * P}{\pi * d * l} \right] \tag{4}$$

where

σ = tensile splitting strength
P = maximum applied load
d = diameter of core
l = length of core

Using the tensile splitting strength from Equation 4, flexural strength is calculated as shown in Equation 5 (Hammitt 1974).

$$\textit{flexural strength} = \sigma * 1.02 + 210 \tag{5}$$

where σ is the tensile splitting strength.

Related studies

Concrete strength relationships (Hammitt 1974)

Hammitt developed a relationship between tensile splitting strength and flexural strength (Equation 5) using 199 test results from six sources. The

correlation, with the accompanying coefficient of determination, is shown in Figure 3. This is also the same correlation that AFCESA uses when determining flexural strength from tensile splitting strength (Equation 5).

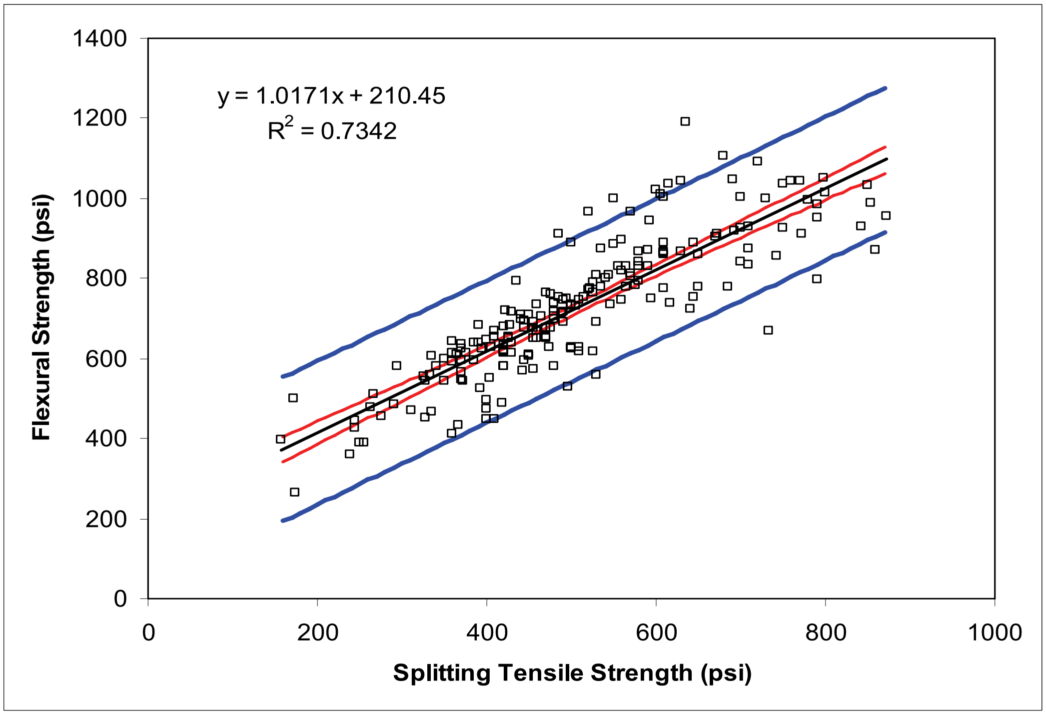

Figure 3. Regression for tensile splitting strength and flexural strength (Hammitt 1974).

This plot shows 95% confidence limits for the estimated flexural strength (blue lines) and the estimated mean flexural strength (red lines). The standard error for the regression was 90 psi. From a single tensile splitting test, flexural strength can be estimated plus or minus approximately 15 psi (a range of 30 psi). The mean flexural strength represents an average response over many trials. Hammitt does not specify whether any of the test results included in his database represented the average of multiple tests (Hammitt 1974). Each reported value of strength will be assumed herein to represent the breaking strength of a single cylinder or beam.

In situ strength measurements

A combined field testing and laboratory study was conducted for the Pavement Technical Assistance Program (PTAP) to evaluate the capabilities of the PSPA, investigate the FFRC test as an alternative to the laboratory tensile splitting test, and to develop test procedures and relationships for the determination of PCC flexural strength for use in pavement structural evaluations. The laboratory testing included using two aggregate types

(crushed limestone and siliceous river gravel (SRG)) and multiple PCC strengths, while the field testing assessed the ruggedness and reliability of the PSPA, provided verification for the laboratory testing, and allowed for the direct correlation of in situ seismic measurements with laboratory measurements. A relationship between measured PSPA modulus and flexural strength was developed from the study as shown, in Figure 4 (Alexander 1996).

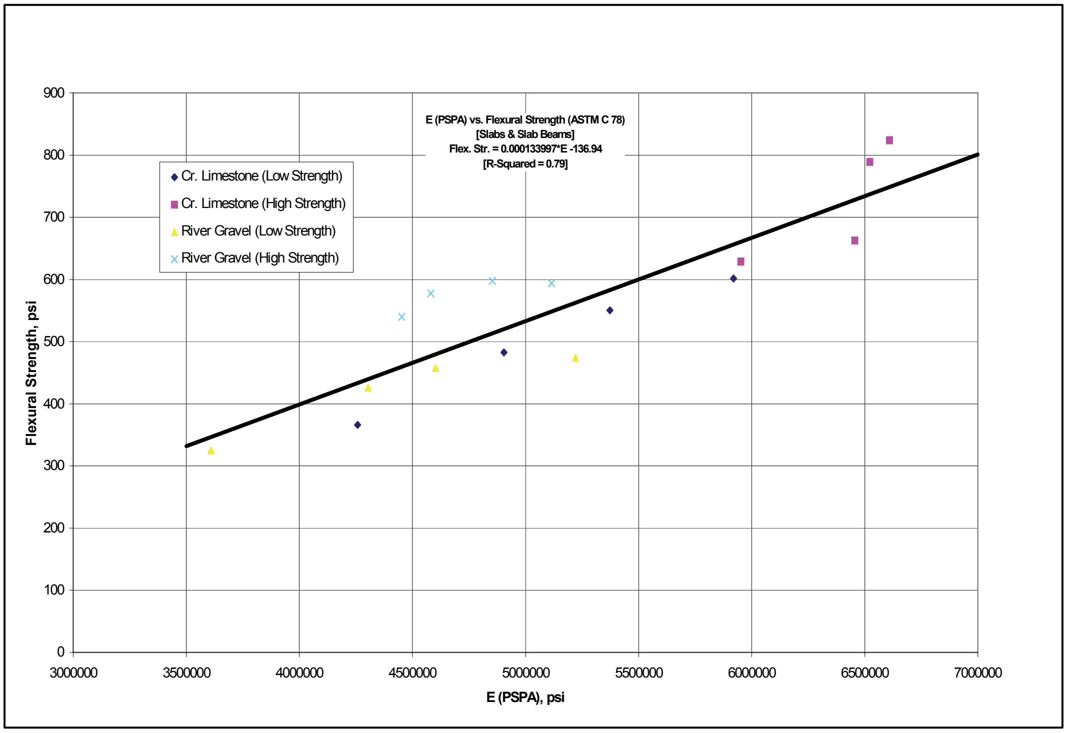

Figure 4. Correlation between PSPA modulus and flexural strength from the 1996 PTAP study (Alexander 1996).

The R-squared value for this relationship was 0.79, and the correlation is shown in Equation 6 (Alexander 1996).

$$flexural\ strength = 0.000133997 * E_{PSPA} - 136.94 \qquad (6)$$

where E_{PSPA} is the measured PSPA modulus.

A relationship between measured FFRC modulus and flexural strength was also developed from the study, as shown in Figure 5.

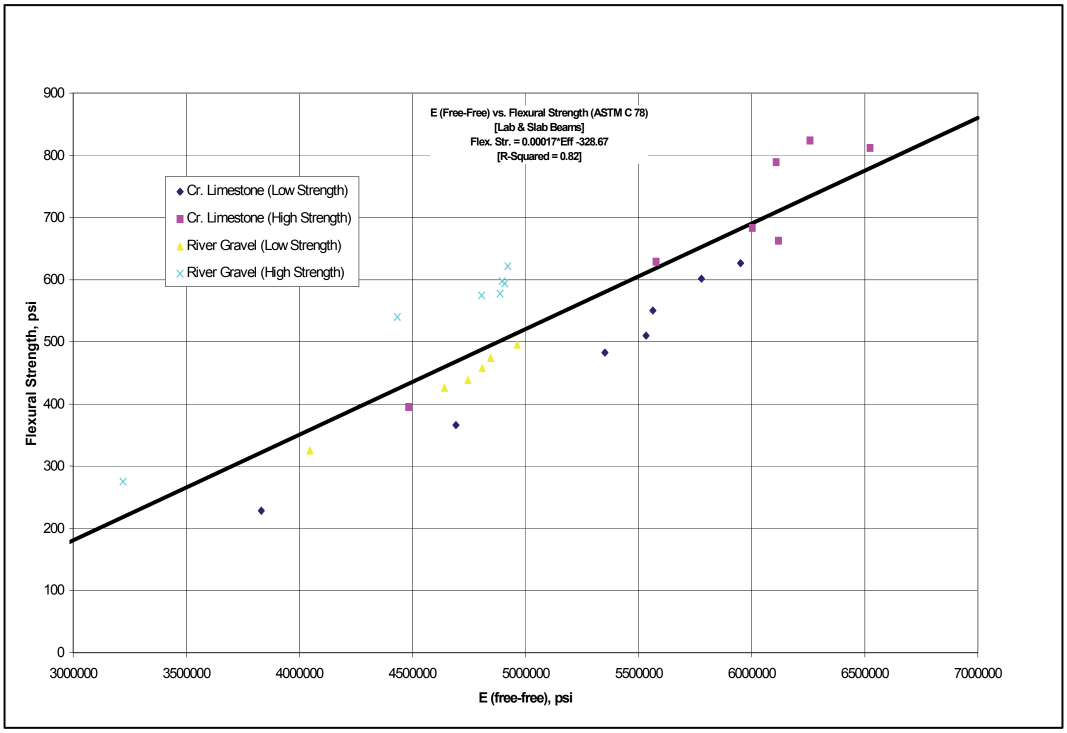

Figure 5. Correlation between FFRC modulus and flexural strength from the 1996 PTAP study (Alexander 1996).

The R-squared value for this relationship was 0.82, and the correlation is shown below (Alexander 1996).

$$flexural\ strength = 0.00017 * E_{FFRC} - 328.67 \qquad (7)$$

where E_{FFRC} is the measured FFRC modulus.

Acceptance criteria based on innovative testing of concrete pavements

A PSPA laboratory study was conducted in 2005 for the Innovative Pavement Research Foundation (IPRF), Washington, DC, as a collaborative effort involving the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, the University of Texas at El Paso, El Paso, TX, and the University of Illinois at Chicago, Chicago, IL, during 2004 and 2005 to implement seismic testing as an acceptance criteria for concrete airfield pavement construction. The procedure consisted of building small-scale slabs using three aggregate types (SRG, granite, and limestone) with multiple mix design deviations and obtaining core samples and beams from the slabs. The PSPA was tested on the slabs at time intervals of 1, 3, 7, 14, and 28 days before the beams and cores were removed. FFRC tests were performed on the beams and the cores; then, a compressive strength

test was performed on the cores. Flexural strength was determined from the beams, and compressive strength was determined from the core samples. The PSPA modulus was correlated to the flexural strength obtained from the FFRC tests (Yuan et al. 2005).

4 Field Testing

Description of test sites and test methods

PSPA evaluations were conducted at two Air Force bases and one Army airfield. In January 2005, the field testing began at Hurlburt Air Force Base in Fort Walton Beach, FL. Field testing continued in February 2005 at Barksdale Air Force Base in Shreveport, LA, and concluded at Phillips Army Airfield in Aberdeen Proving Ground, MD, in April 2005. During each Air Force Base evaluation, two PSPAs, a core hole drill, and a falling weight deflectometer were used, while one PSPA and a FWD were used during the Army airfield evaluation. Free-free resonant column tests were conducted on all core samples. Figure 6 shows the PSPA, core hole drill, and the FWD from an Air Force Base evaluation, and Figure 7 shows a FFRC test on a core sample.

Figure 6. PSPA, core hole drill, and FWD.

Hurlburt Air Force Base

The pavements at HAFB consisted primarily of portland cement concrete surfaces with some asphalt concrete surfaces. The pavements were broken up into 55 features, of which 43 were PCC features and 12 were AC features. On the PCC features, both PSPAs were used on the same slab for three test repetitions per device at most of the core hole locations and at selected FWD locations. On the AC pavements, the PSPA tests were

Figure 7. Running the FFRC on a core sample.

performed as close to the core hole and FWD locations as possible. Ninety-nine core samples were taken at HAFB, and at least one PSPA was used at every core hole location.

Barksdale Air Force Base

The pavements at BAFB consisted mostly of PCC (6 to 13 in.) over PCC (6 to 13 in.). There were 102 PCC features, 11 AC features, and 2 double bituminous surface treated features. Sixty-six core samples were taken, and one PSPA was utilized at each core hole location. A second PSPA was used one slab adjacent to the FWD testing slab. Figure 8 and Figure 9 show the PSPA being tested at the core hole and FWD locations, respectively.

At least two repetitions of the PSPA measurements were completed at the same time as the FWD tests. On the AC pavements, the PSPA was tested as close to the core hole and FWD locations as possible.

Phillips Army Airfield

The pavements at PAAF consisted mostly of AC pavements. The airfield had 29 features that were tested, and only 3 were PCC features. The surface condition of the pavements at PAAF ranged from fair to poor, and the AC pavements consisted mainly of rough, weathered AC. No core samples were taken, and only one PSPA was used. At least two test repetitions were performed at the same time and close to every FWD test location. The

Figure 8. Testing the PSPA at the core hole location.

Figure 9. Testing the PSPA one slab adjacent to the FWD test slab.

PSPA was tested every 100 ft on the AC surfaces and approximately every fifth slab on the PCC pavements.

Additional testing

Additional testing was conducted on a PCC slab located under Hangar 4 at ERDC and a PCC slab from BAFB in November 2005 and March 2006, respectively. The purpose of this additional testing was to compare the flexural strength determined from the correlation of the PSPA modulus (Equation 8) with the flexural strength determined from the correlation of the tensile splitting strength (Equation 5) using the actual flexural strength determined from breaking the beams in the laboratory. The Hangar 4 slab consisted of 18 in. of PCC, and the BAFB slab consisted of the top 8 in. of a

PCC slab located on the parking apron between core holes 48 and 50 of the 2005 AFCESA pavement evaluation. The PSPA was run at several locations on the slabs to determine an average modulus before the slabs were brought to the concrete laboratory for beam and core removal and testing. A total of eight beams (four from the top, four from the bottom) and three cores were removed from the Hangar 4 slab. Five beams and three cores were removed from the BAFB slab. The beams were broken in order to determine the flexural strength of the concrete, and tensile splitting tests were conducted on the cores. Flexural strength was estimated from the tensile splitting test results using the correlations that AFCESA uses (Equation 5). Figure 10 shows the PSPA on the Hangar 4 slab prior to removal, and Figure 11 shows beams being sawn from the BAFB slab in the ERDC concrete laboratory.

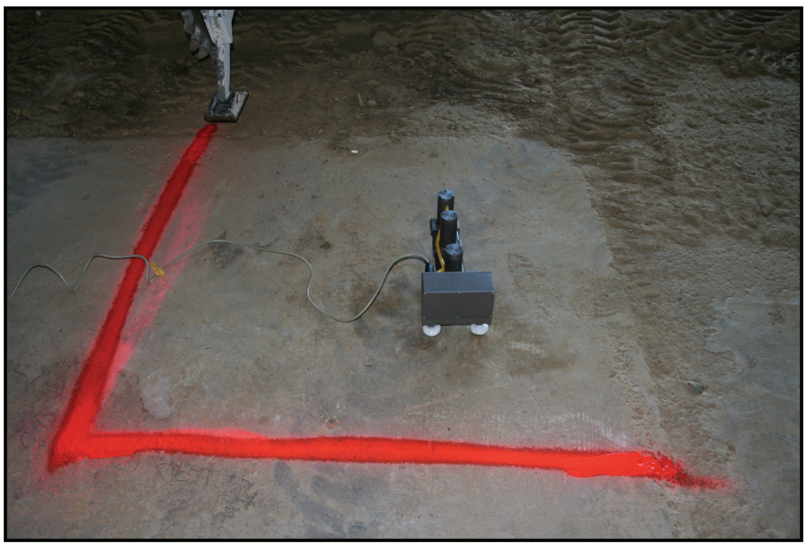

Figure 10. PSPA testing on the Hangar 4 slab.

Figure 11. Sawing beams from the BAFB slab.

5 Summary of Results and Findings

In the analysis, it is assumed that the PSPA was run on the same slab as the core hole and the FWD because an exact testing procedure was not followed at each test site. Raw data taken at HAFB, BAFB, and PAAF are given in Appendixes A, B, and C, respectively.

Hurlburt and Barksdale Air Force Bases

Two PSPA devices were used at HAFB and BAFB. Figure 12 shows the repeatability and reliability of the PSPA by comparing the measured modulus values of the two PSPAs at the same locations. The PSPA moduli shown on the plot are the average of all the test repetitions (normally, two to three) at each location. The modulus values are close to the line of equality, which shows that PSPA 1 and PSPA 2 provided comparable modulus values.

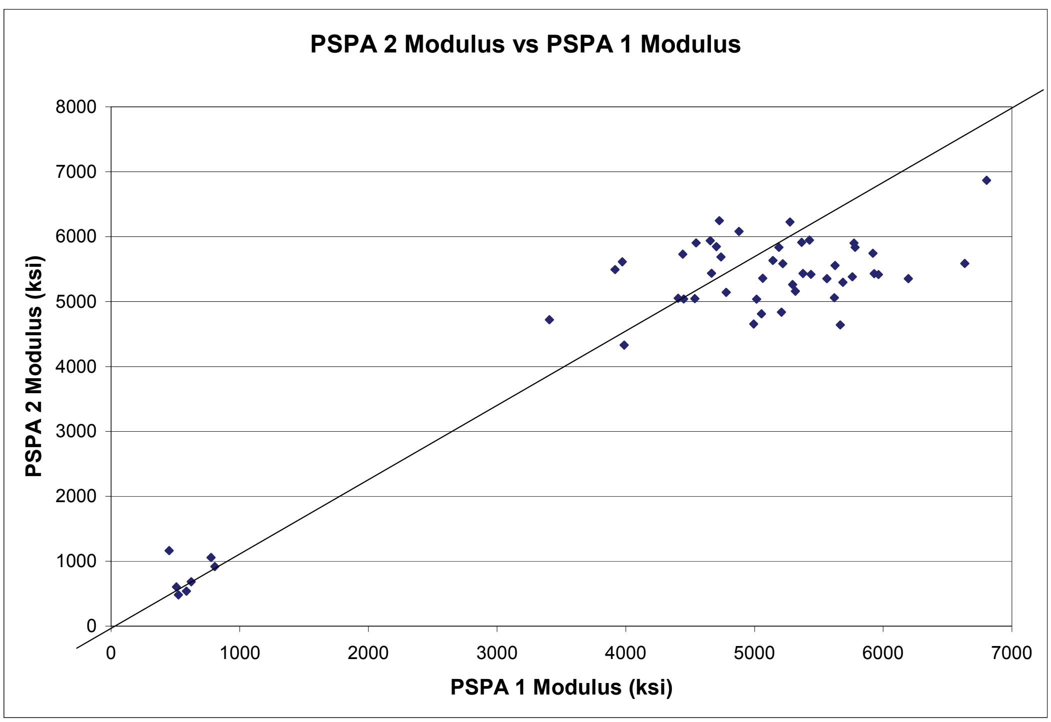

Figure 12. Comparing PSPA modulus values at the same locations at HAFB and BAFB.

FWD and FFRC tests were conducted along with the PSPA tests at HAFB and BAFB. All three test methods give surface modulus values. Figure 13 and Figure 14 show the trends associated with the three test procedures

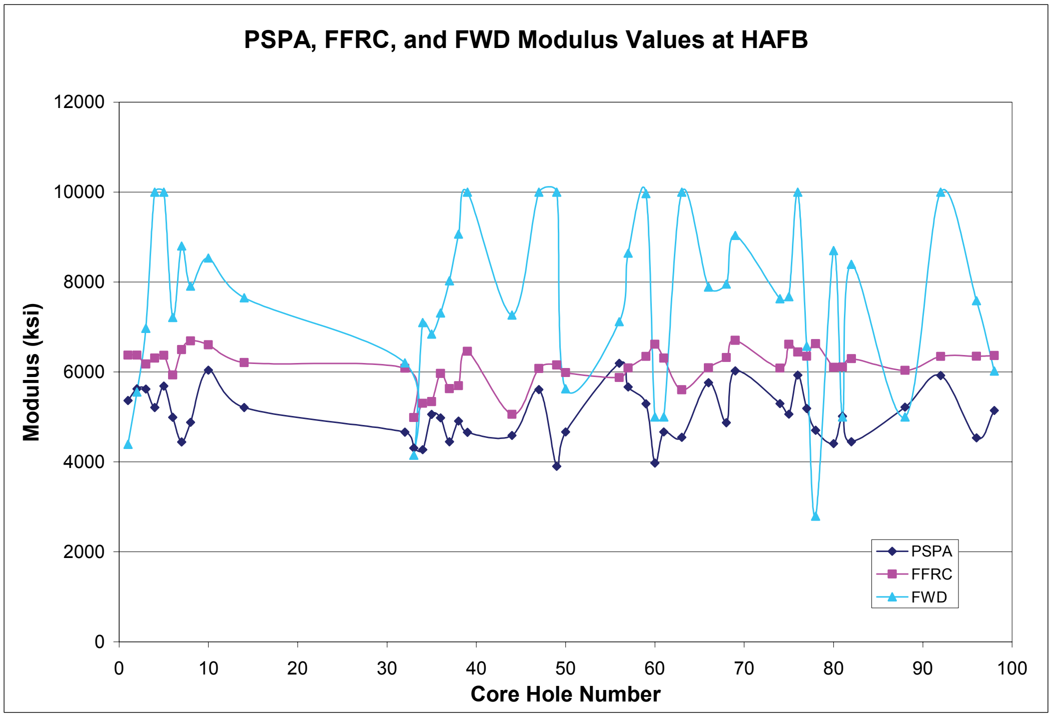

Figure 13. Modulus value trends at HAFB.

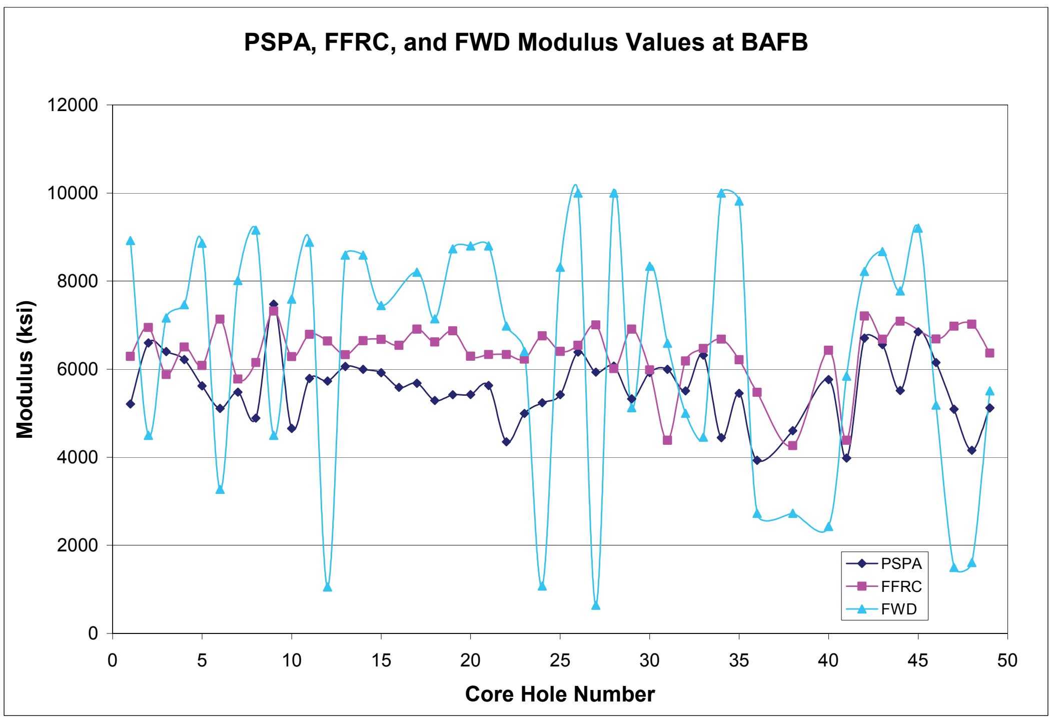

Figure 14. Modulus value trends at BAFB.

conducted at HAFB and BAFB, respectively. The data shown in the graphs were collected at the PCC pavement core hole locations.

Figure 13 and Figure 14 show similar modulus value trends. The FWD includes the deflection of the entire pavement structure; however, it is also used to estimate the surface pavement modulus by means of backcalculation. It is difficult to obtain representative modulus values of surface layers with the FWD. As shown in Figure 13 and Figure 14, the FWD tests reach modulus value limits of 10,000 ksi, whereas the PSPA values are between approximately 4000 and 7000 ksi. The PSPA modulus values are closer to the typical modulus range of 4000 to 6000 ksi for PCC pavements. Although it is not shown in Figure 13 and Figure 14, 10% must be added to the PSPA modulus in order to compare it directly with the FFRC modulus. This is attributed to the fact that the PSPA measures modulus from the top portion of the surface pavement, while the FFRC measures modulus from the entire depth of the surface pavement. Thus, it appears from the trends shown in Figure 13 and Figure 14 that the PSPA modulus values are more reasonable than many of the FWD backcalculated values for the reasons discussed previously.

Phillips Army Airfield

The PSPA was tested in addition to the FWD at PAAF. The pavements at PAAF consist mainly of coarse AC in poor condition; however, the PCC pavements were in fair condition. There were small, hairline cracks and medium- to high-severity weathering on most of the AC pavements, which prevented the PSPA from measuring repeatable modulus values within each feature. Figure 15 and Figure 16 show the modulus values at each feature for AC pavements and PCC pavements, respectively, from the FWD and the PSPA at PAAF. The standard deviations of the PSPA modulus values from the AC pavements in Figure 17 show the wide range of data given from each feature. The PSPA did not provide valid measurements on the severely cracked pavement.

As discussed previously, the PSPA gives more reasonable values than the FWD for the PCC pavement features. From Figure 16, two of the FWD surface modulus values are above the normal PCC modulus values of 4000 to 6000 ksi, while one FWD surface modulus value is below the norm.

Flexural strength relationship

The data from the PSPA laboratory studies conducted in 1996 (PTAP) and 2005 (IPRF) were combined in order to develop a relationship between

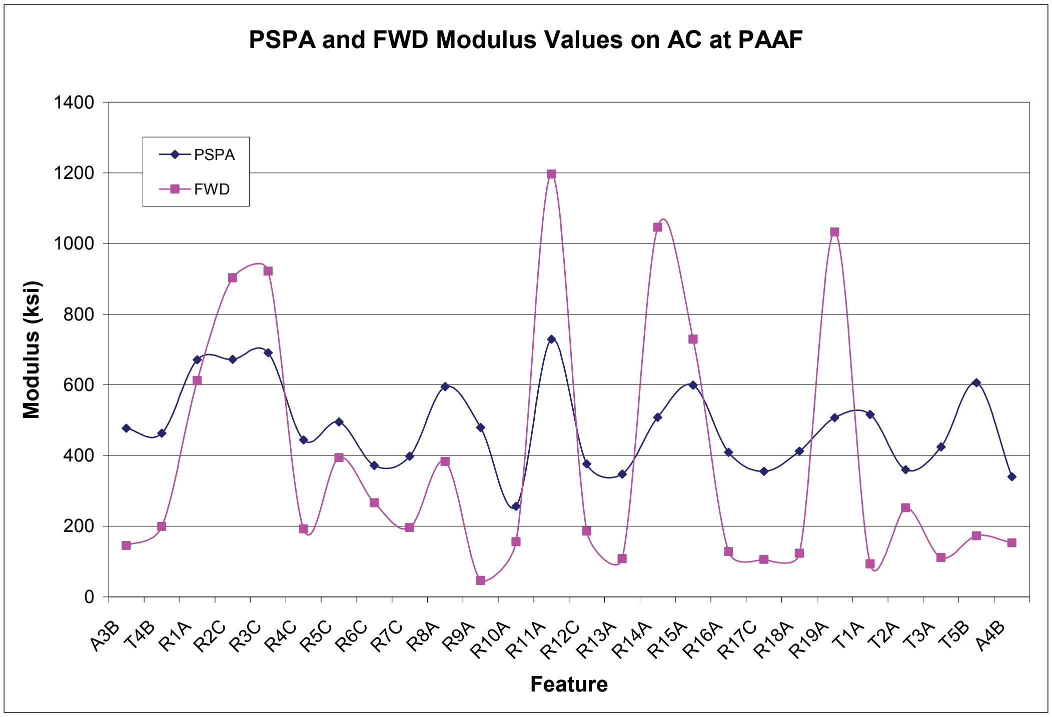

Figure 15. Modulus values on AC pavements at PAAF.

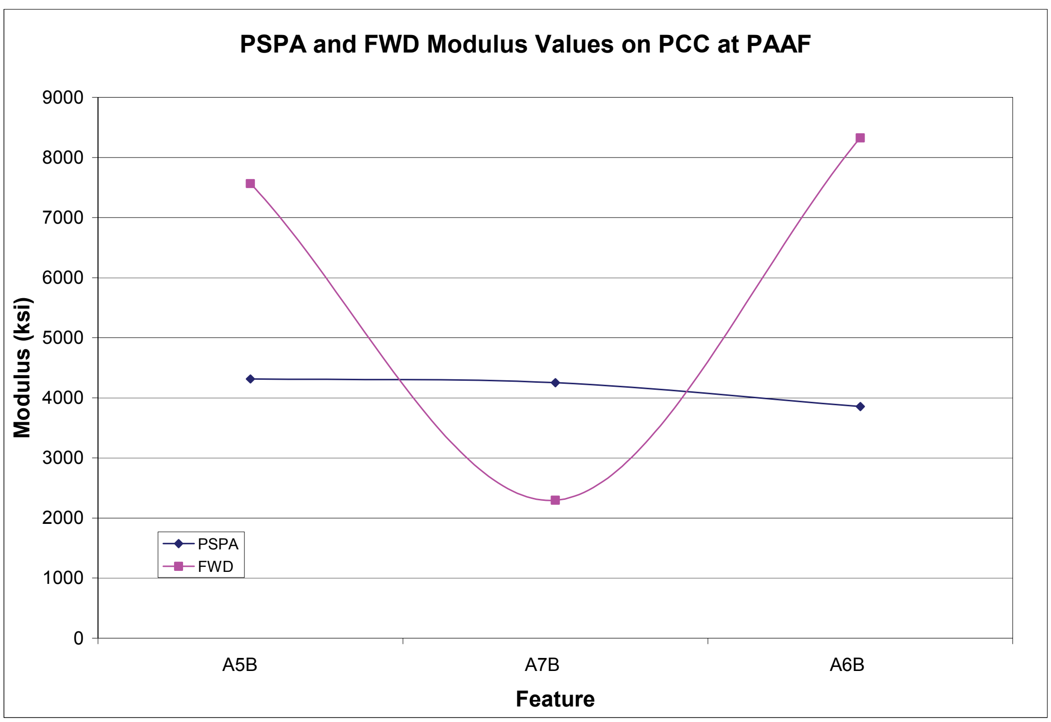

Figure 16. Modulus values on PCC pavements at PAAF.

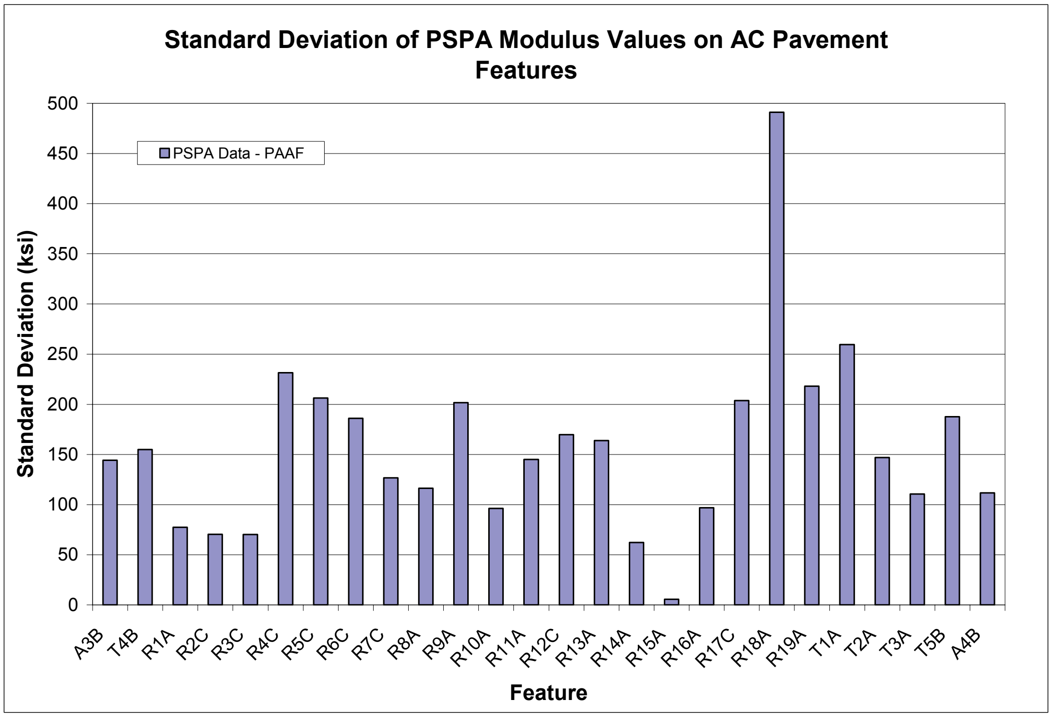

Figure 17. Standard deviations of PSPA modulus values on AC pavements at PAAF.

the PSPA modulus and flexural strength for PCC pavements. The flexural strength values from these studies were measured values from beams that were prepared and tested in the laboratory. Appendix D gives the data from the 1996 PTAP and 2005 IPRF studies that were used to determine the relationship. Figure 18 shows the correlation that was developed using four types of aggregates.

As shown on the plot, the R-squared value is 0.53, and the correlation is shown in Equation 8.

$$flexural\ \ strength = 0.12 * E_{PSPA} \tag{8}$$

where E_{PSPA} is the measured PSPA modulus.

Additional testing findings

The slabs obtained from Hangar 4 and BAFB were taken to the concrete laboratory at the ERDC for additional testing after the field tests using the PSPA. Beams and cores were removed from the slabs to determine the

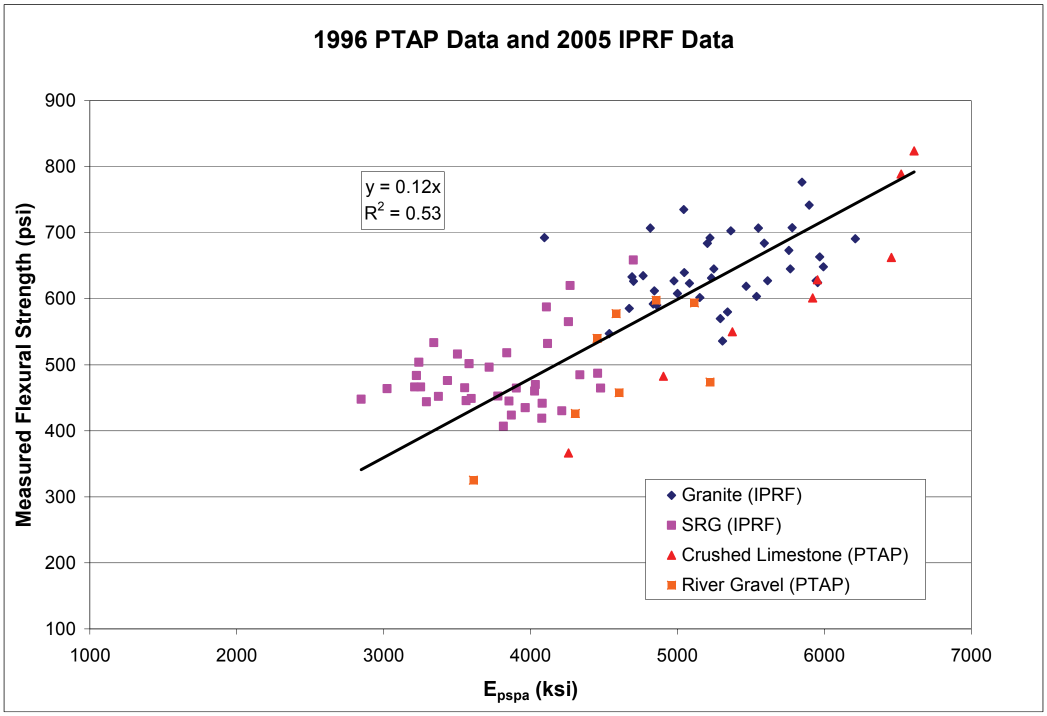

Figure 18. Correlation between the PSPA modulus and flexural strength.

flexural strength from breaking the beams and from conducting tensile splitting tests on the cores.

Figure 19 shows the flexural strength data of HAFB computed from the tensile splitting tests and PSPA correlations at each core hole, and Figure 20 shows the same type of flexural strength data from BAFB. The flexural strength computed from the tensile splitting is from Equation 5, and the flexural strength from the PSPA is computed from Equation 8.

The plots show that the average flexural strength from the PSPA correlation (Equation 8) is consistently around 20% lower than the average flexural strength from the tensile splitting correlation (Equation 5).

The same consistency was found when comparing the flexural strengths of the two correlations from the Hangar 4 slab and the BAFB slab, as shown in Table 1. More importantly, the average flexural strength obtained from the PSPA modulus correlation is closer to the actual average flexural strength determined from the beam tests in the laboratory than the flexural strength from the tensile splitting correlation.

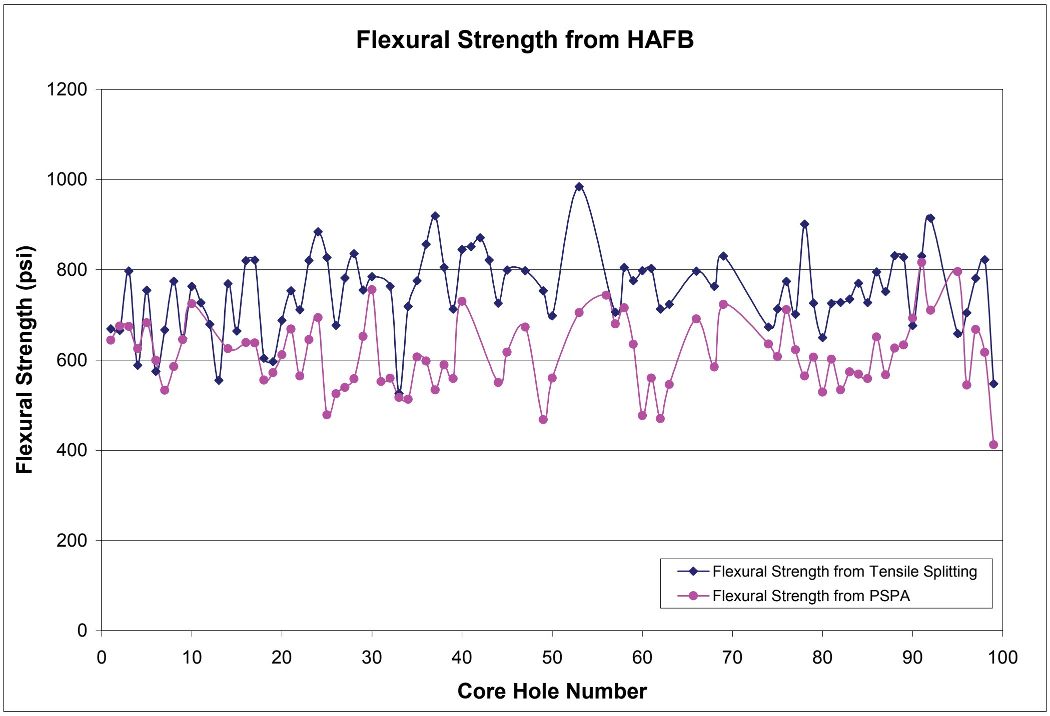

Figure 19. Flexural strength from PSPA and tensile splitting correlations at HAFB.

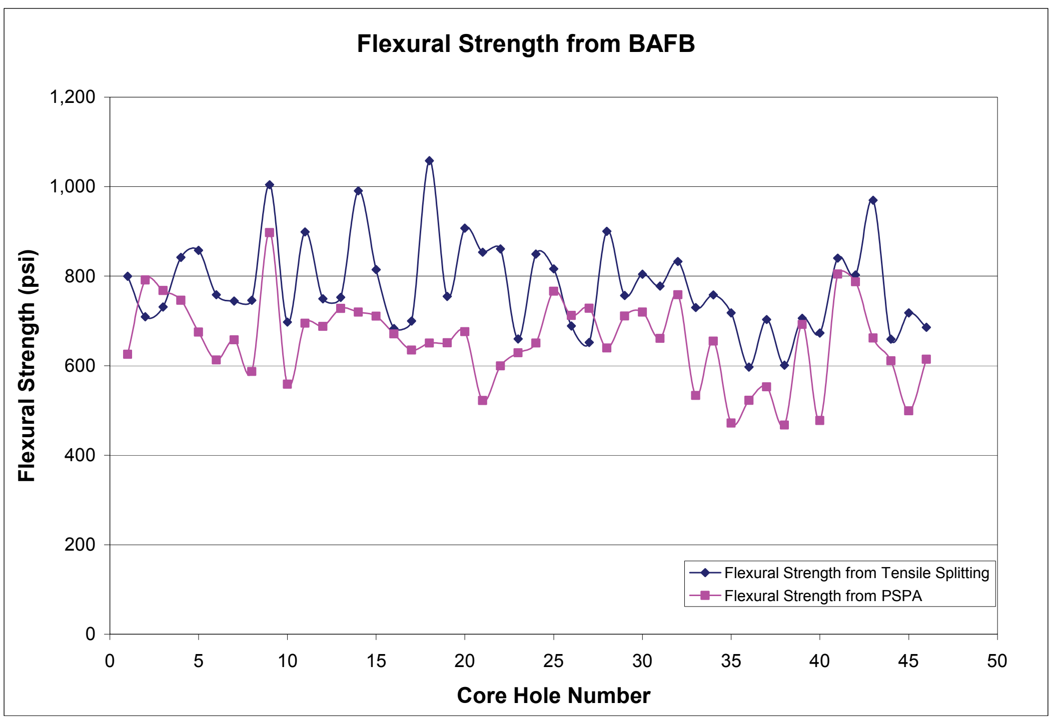

Figure 20. Flexural strength from PSPA and tensile splitting correlations at BAFB.

Table 1. Flexural strength values from field and laboratory tests.

Test Site	Average Flex Strength (psi)			Ratio (PSPA: TS)
	Beam Tests	PSPA	Tensile Splitting	
HAFB	------	612	751	0.81
BAFB	------	656	778	0.84
Hangar 4 Slab	547	653	788	0.83
BAFB Slab	814	726	936	0.78

PSPA ruggedness

Field experience has shown that the PSPA does not perform to its expectations on rough, damaged AC pavements. The PSPA did not adapt well to most of the pavements at PAAF because of their poor surface condition. The contact between the transducer tips and the AC pavement was poor because of the cracking and weathering. The AC surface conditions caused the waveforms in the phase diagrams to not match up with the best fit line, which affected the reliability and repeatability of the seismic modulus on each feature.

The rubber pads on the bottom of the receivers and the source on the PSPA, which are generally referred to as the feet, can easily be replaced when they begin to wear. Although the appearance of the feet normally varies at the end of each testing day depending upon the condition of the pavement surface, experience has shown that the feet of the PSPA begin to deteriorate after approximately 2 days of testing in the field. Figure 21 shows a damaged rubber pad on the bottom of the source after about 3 days of working in the field. The metal foot is exposed; therefore, testing should stop until the rubber pads are replaced.

The battery life of the PSPA is about 3 to 5 field testing days. The battery life is given when the SpaManager software is opened. Also, when the PSPA starts giving odd modulus values and suspect waveforms, this may be an indication that the batteries need to be replaced.

Determining sample size

Often, it is not necessary to test the PSPA several times in a feature. The properties of the pavement within a feature can be determined with a few PSPA tests without sacrificing significant accuracy from data evaluated with a large number of tests. With a known standard deviation and

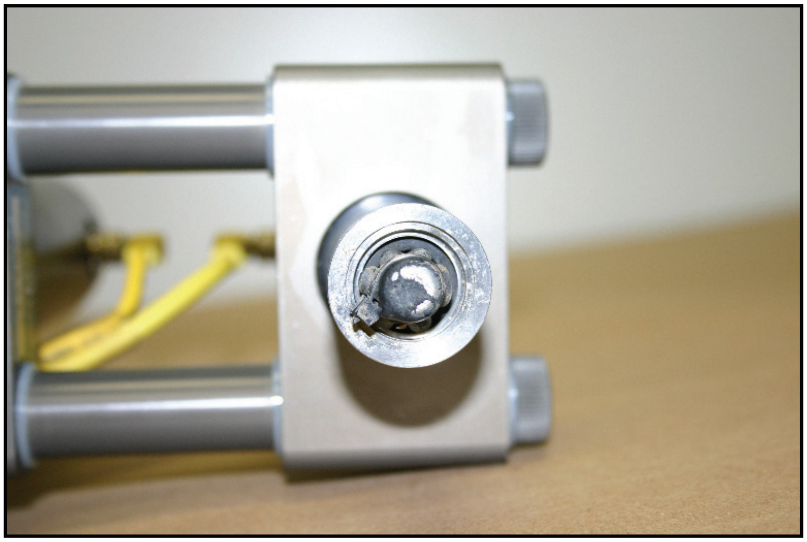

Figure 21. Worn rubber pads from field testing.

confidence interval, the number of PSPA tests to run in a feature can be determined using the following equation (iSixSigma 2000-2005):

$$n = \left[\frac{Z_{\alpha/2} * \sigma}{E} \right]^2 \tag{9}$$

where

n = number of samples
$Z_{\alpha/2}$ = critical value of an area
σ = standard deviation
E = margin of error

Figure 22 shows a distribution curve with an area of $\alpha / 2$, shown in the shaded areas.

The section to the right of $Z = 0$ and to the left of $Z_{\alpha/2}$ is used to calculate Z as shown (iSixSigma 2000-2005):

$$Z = 0.5 - \alpha/2 \tag{10}$$

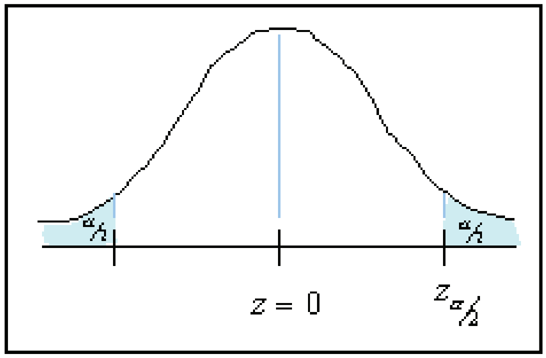

Figure 22. Sample distribution curve (iSixSigma 2000-2005).

Based on literature reviews of past projects, the average standard deviation of flexural strength values tended to range from 40 to 80 psi (NNECPA 2000). Based on the results of the evaluations at HAFB and BAFB, the typical standard deviations of flexural strengths were around 50 psi. When using a confidence level of 95%, α is 1-0.95 or 0.05, and ordinate Z at an area of $\alpha/2$ or 0.025 is calculated to be 0.475. Using the calculated Z and the Table of the Standard Normal Distribution (see Appendix E), $Z_{\alpha/2}$ is determined to be 1.96. After using these values in Equation 9, n is determined to be 3.84, so four tests need to be run in a feature to have a 95% confidence.

The AFCESA generally takes one or two core samples per feature, which results in a confidence level of about 68% and 84%, respectively. These one or two core samples are used to determine the concrete properties of the entire feature. Table 2 shows the sample confidence based on an average standard deviation of 50 psi and a margin of error of 50 psi.

Table 2. Percent confidence of sample numbers.

n	Confidence (%)
1	68
2	84
3	91
4	95

Four tests are needed to determine the pavement properties of a feature with a 95% confidence level. The PSPA can achieve four tests with a 95% confidence level considerably quicker than the AFCESA pavement evaluation team can obtain one core sample with only a 68% confidence level.

Determining thickness

Estimating the thickness of PCC and AC pavements was approached using two different methods, Tback and WESDEF. The Tback software estimates thickness using the load and deflections from the FWD tests and the modulus values from the PSPA. The WESDEF software, developed by researchers at the ERDC, estimates thickness using the data from the SpaManager software. Both programs are promising, but have proven to be unsuccessful thus far. Additional research could potentially yield the desired accuracy.

6 Conclusions and Recommendations

The ERDC was tasked by the AFCESA to evaluate the PSPA on military airfield PCC and AC pavements. This report addresses field testing performed to assess the ruggedness of the device, develop new testing procedures, and derive relationships between the PSPA modulus and flexural strength. Conclusions from the evaluations and recommendations for using the PSPA on military airfield pavements are provided in the following text.

Conclusions

The following conclusions resulted from the evaluation of the PSPA from January to April 2005:

a. The PSPA provides a reliable measure of PCC modulus.
b. A correlation between the PSPA modulus and flexural strength was developed based on data from the 1996 Pavement Technical Assistance Program and 2005 Innovative Pavement Research Foundation studies:

$$\textit{flexural strength} = 0.12 * E_{PSPA}$$
$$R^2 = 0.53$$

c. The average flexural strength obtained from the PSPA modulus correlation is closer to the actual average flexural strength determined from the beam tests in the laboratory than the flexural strength from the tensile splitting correlation.
d. The flexural strength obtained from the PSPA measurements is consistently around 20% less than comparable flexural strength obtained from tensile splitting tests.
e. The battery life of the PSPA is approximately 3 to 5 testing days, and the batteries should be replaced routinely.
f. The rubber pads on the feet of the PSPA show wear and tear after about 1 or 2 days of testing and should be checked and replaced routinely.
g. The PSPA will not provide valid measurements on severely cracked pavements.
h. Thickness estimates from the PSPA are not accurate enough for evaluating pavement; however, additional research could potentially yield the desired accuracy.

Recommendations

Based upon tests performed at HAFB, BAFB, and PAAF and data from the 1996 PTAP and 2005 IPRF projects, the following recommendations are offered:

a. Use the following correlation when relating the PSPA modulus to flexural strength:

$$\textit{flexural strength} = 0.12 * E_{PSPA}$$

b. Replace the batteries after approximately 3 to 5 full days of field testing.
c. Inspect the rubber pads on the feet of the PSPA after every day of testing.
d. Remove and replace the rubber pads on the bottom of the source and the receivers when they begin to show wear and tear, generally every 1 to 2 days.
e. Test the PSPA at least four times in a feature with three test repetitions at each location for a 95% confidence level.

Research recommendations

The following research recommendations were developed based on the results of the PSPA evaluation:

a. More data (pavements consisting of varying aggregates) are needed to develop a stronger correlation between the flexural strengths of beams to PSPA modulus. Additional data will help remove error from the current correlation (Equation 8), thus allowing for a more accurate relationship.
b. Simple techniques are desired for obtaining thickness. Research needs to be conducted for alternative methods of nondestructively estimating pavement thickness.

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Appendix A: Raw Data, Hurlburt Air Force Base (HAFB)

Table A1. PCC pavements core hole raw data, HAFB.

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
A02B	1	1	5340	5350	5410				
	2	5	5600	5620	5660				
	3	18	5640	5610	5610				
T01A	4	38	5190	5190	5250				
	6	34	4960	4990	5030				
A01B	5	57	5690	5670	5700				
T02A	7	62	4450	4460	4420				
	9	68	5820	5410	4900	5570	5480	5450	
T04A	8	72	4890	4870	4880				
	10	88	6020	6030	6070				
A06B	14	134	5190	5230	5210				
A08B	16		5340	5280	5350				
	17		5290	5380	5280				
A09B	18		4610	4640	4640				
A11B	19		4790	4790	4720				
A12B	20		4720	5880	4880	5060	4950		
A10B	21		5620	5570	5530				
	22		4400	4840	4810	4760	4710		
A14B	23		5350	5420	5360				
	24		5700	5720	5700	6010			
A15B	25		3970	3980	4010				
T10A	26		4370	4390	4370	4380	4380	4370	
	28		4490	4480	4990				
	29	265	5160	5230	5120	5760	5660	5690	
	99		3350	3420	3450				
A25B	27		4450	4460	4570				
T09A	30		6310	6290	6300				
	31		4620	4590	4600				
A20B	32	279	4660	4680	4650				
	33	284	4290	4290	4350				
A15B	34	300	4280	4280	4260				
A17B	35	309	5230	4880	4750	5370			
	37	322	4460	4460	4430				

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
A16B	36	315	5070	4760	5110				
	38	335	4910	4930	4890				
A29B	39	340	3840	3720	3670	4820	5570	5510	5470
	40		6080	6080	6090				
A21B	44	378	4580	4520	4660				
T07C	45		5030	5220	5190				
	47	395	5080	6440	5460	5460			
A23B	49	415	3490	4010	4010	4090			
	50	410	4640	4660	4700				
T15C	53		4680	5250	5260	5440	6920	6760	6830
A26B	56	507	6310	6320	5880	6200	5990	6470	
A28B	57	517	5220	5910	5870				
	58		5460	6190	6240				
	59	519	5390	4930	5500	5450			
A27B	60	547	3940	4000	3980				
	61	551	4680	4660	4660				
	62	557	3890	3930	3930				
A24B	63	440	4530	4540	4570				
T03C	68	113	4840	4870	4910				
	69	109	6050	6080	5950				
R02A	74	621	5110	5300	5480				
	75	635	4990	5170	5030				
	76	641	5880	5900	6010				
	77	636	5200	5170	5200				
R04C	78	651	4680	4760	4670				
	81	660	5030	5020	5000				
	83		4760	4780	4800				
	86		6040	5130	5110				
	88	730	5170	5230	5260				
	89		5320	5270	5240				
R03C	79		5010	5060	5090				
	80	653	4350	4410	4460				
	82	681	4440	4450	4460				
	84	682	4720	4760	4740				
	85	683	4640	4680	4650				
	87		4290	4950	4940				
	90	685	5710	5790	5820				
R11A	91		6820	6800	6790				
R12A	92	743	5900	5920	5940				

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
T18C	95		6620	6650	6630				
	96	770	4570	4500	4540				
T19C	97	805	5540	5590	5560				
T05C	98	791	5130	5150	5150				

Table A2. AC pavements core hole data, HAFB.

Feature	Core Hole	PSPA Modulus (ksi)		
		Test 1	Test 2	Test 3
T06C	46	834	816	819
T08C	48	508	511	514
T11C	51	463	463	463
T14C	52	516	507	504
T16C	54	504	504	513
	55	450	447	456
T13C	64	576	590	590
	65	613	620	633
T12A	67	615	619	625
R01A	71	776	776	779
	73	794	814	809
O02C	72	532	517	520

Table A3. PCC Pavements, FWD Raw Data, HAFB

Feature	FWD Drop Number	PSPA Modulus (ksi)					
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
A02B	1	5340	5350	5410			
	3	4600	4610	4660			
	4	5380	5410	5420	5470		
	5	5600	5620	5660			
	6	5520	5610	5570			
	7	5130	5150	5160			
	8	4730	4790	4800			
	9	5490	5640	5670			
	10	5360	5580	5550			
	11	6420	6410	6420			
	12	5730	5750	5730			
	13	4820	4830	4870			
	14	4410	4390	4450			
	15	5240	5280	5230			
	16	5230	5250	5220			
	17	5670	5690	5650			
	18	5640	5610	5610			
	19	5250	5330	5350			
	20	5640	5660	5690			
	21	5160	5190	5190			
	22	5910	5920	5920			
	23	6240	6460	6060			
	24	5860	5850	5850			
	25	5670	5600	5600			
	26	5890	5870	5890			
	27	5020	5040	4980			
	28	5400	5360	5380			
	29	5690	5710	5730	5700		
	30	4590	5040	4960			
T01A	31	4590	4330	4350			
	32	5340	5330	5340			
	33	5440	5420	5460			
	34	4960	4990	5030			
	35	5040	5070	5040			
	36	5500	5410	5470			

Feature	FWD Drop Number	PSPA Modulus (ksi)					
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
T01A	37	5540	5530	5550			
	38	5190	5190	5250			
	39	5330	5330	5370			
	40	4760	4770	4780			
	41	5290	5190	5170			
	42	5810	5750	5850	6010		
	43	5190	5320	5340			
	44	5400	5410	5390			
	45	5440	5460	5460			
	46	4830	4700	4670			
	47	4640	4660	4680	4710	4220	
A01B	48	5080	5060	5070			
	49	5040	5070	5070			
	50	5280	5310	5320			
	51	4740	4780	4740			
	52	5810	5800	5790			
	53	5290	5290	5280			
	54	4760	5350	4700			
	55	5240	5290	5260			
	56	5540	5550	5560			
	57	5690	5670	5700			
	58	5430	5390	5400			
	59	5550	5520	5560			
	60	5170	5140	5160			
T02A	61	4560	5110	5100	5140		
	62	4450	4460	4420			
	63	5050	5080	5050			
	64	5810	4870	4870	4860		
	65	6070	6120	6120			
	66	5080	5050	5050			
	67	4060	4080	4060			
	68	5820	5410	4900	5570	5480	5450
	69	6130	6020	6060			
	70	5450	5490	5530			
	71	5440	5320	4910	4900		
	72	4890	4870	4880			
T04A	84	5430	5760	5200	5190		
	86	6400	6380	6210	6200		
	88	6020	6030	6070			

Feature	FWD Drop Number	PSPA Modulus (ksi)					
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
T03C	107	5660	5650	5650			
	109	6050	6080	5950			
	111	5190	5150	5170			
	112	4640	4660	4650			
	113	4840	4870	4910			
	115	5390	5390	4990			
	117	4620	4560	4600			
A03B	134	5190	5230	5210			
	138	4210	4240	4220			
	145	5740	5690	5760			

Table A4. FFRC raw data, HAFB.

Feature	Core Hole	Diameter (in.)	Length (in.)	Frequency	Modulus (ksi)
A02B	1	5.75	12.50	6739	6375
	2	5.75	13.00	6481	6376
	3	5.75	12.50	6634	6177
T01A	4	5.75	15.50	5406	6308
	6	5.75	15.75	5161	5935
A01B	5	5.75	14.62	5758	6370
T02A	7	5.75	15.50	5486	6497
	9	5.75	14.75	5854	6698
T04A	8	5.75	14.75	5852	6693
	10	5.75	15.25	5623	6605
	11	5.75	15.00	5855	6929
A07B	12	5.75	15.00	5625	6397
	13	5.75	15.75	5227	6089
A06B	14	5.75	14.50	5735	6212
	15	5.75	14.75	5529	5975
A08B	16	5.75	14.00	6304	6997
	17	5.75	14.00	5832	5988
A09B	18	5.75	16.50	5169	6535
A11B	19	5.75	13.37	5721	5259
A12B	20	5.75	8.75	8841	5377
A10B	21	5.75	15.25	5680	6739
	22	5.75	15.00	5675	6510
A14B	23	5.75	11.00	7668	6391
	24	5.75	11.87	7213	6591
T10A	26	5.75	11.87	6509	5368
	28	5.75	11.87	7194	6556
	29	5.75	11.87	6898	6029
	99	5.75	11.87	6103	4718
A25B	27	5.75	11.87	6905	6040
T09A	30	5.75	11.87	7133	6445
A20B	32	5.75	10.87	7567	6083
	33	5.75	9.75	7642	4987
A15B	34	5.75	11.00	6986	5305
A17B	35	5.75	9.00	8568	5342
	37	5.75	9.75	8120	5631
A16B	36	5.75	11.87	6862	5966
	38	5.75	12.00	6636	5697
A29B	39	5.75	11.00	7710	6462
	40	5.75	9.00	9531	6611

Feature	Core Hole	Diameter (in.)	Length (in.)	Frequency	Modulus (ksi)
A18B	41	5.75	5.87	13420	5575
	42	5.75	7.75	10703	6181
A19B	43	5.75	10.87	7481	5945
A21B	44	5.75	8.87	8457	5056
T07C	45	5.75	8.00	10571	6425
	47	5.75	9.00	9141	6080
A23B	49	5.75	10.00	8277	6155
	50	5.75	9.00	9071	5988
T15C	53	5.75	6.87	12089	6206
A26B	56	5.75	10.87	7437	5877
A28B	57	5.75	12.00	6862	6092
	58	5.75	12.00	7273	6843
	59	5.75	12.00	7003	6344
A27B	60	5.75	8.87	9669	6615
	61	5.75	10.00	8378	6307
	62	5.75	9.87	8116	5771
A24B	63	5.75	11.87	6651	5605
T17C	66	5.75	11.87	6939	6095
T03C	68	5.75	12.00	6990	6320
	69	5.75	11.87	7274	6704
R02A	74	5.75	12.00	6858	6085
	75	5.75	12.00	7152	6617
	76	5.75	11.87	7133	6445
	77	5.75	11.87	7081	6352
R03C	78	5.75	7.00	12273	6631
	82	5.75	11.87	7050	6297
	84	5.75	11.75	7083	6223
	85	5.75	11.75	7219	6464
	87	5.75	11.87	7167	6508
	90	5.75	12.00	7158	6629
R04C	79	5.75	10.87	7588	6112
	80	5.75	12.00	6868	6102
	81	5.75	6.87	11998	6113
	83	5.75	6.87	12098	6214
	86	5.75	11.00	7609	6294
R04C	88	5.75	5.87	13951	6035
	89	5.75	7.00	12976	7413
R11A	91	5.75	12.00	7341	6972
R12A	92	5.75	9.87	8512	6347

Feature	Core Hole	Diameter (in.)	Length (in.)	Frequency	Modulus (ksi)
T18C	95	5.75	11.87	7148	6473
	96	5.75	11.87	7083	6351
T05C	98	5.75	10.00	8417	6366

Table A5. PSPAs raw data, HAFB.

Feature	Core Hole	FWD Drop Number	PSPA 1 Modulus (ksi)							PSPA 2 Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
A02B	1	1	5340	5350	5410					5920	5890	5930				
	2	5	5600	5620	5660					6180	5330	5360	5350			
	3	18	5640	5610	5610					5050	5060	5070				
T01A	4	38	5190	5190	5250					4690	4750	5070				
	6	34	4960	4990	5030					4640	4670	4650				
A01B	5	57	5690	5670	5700					4990	5180	5220	5450	5490	5440	
T02A	7	62	4450	4460	4420					5470	5640	6510	5860	5800	5610	5220
	9	68	5820	5410	4900	5570	5480	5450		5160	5380	5720				
T04A	8	72	4890	4870	4880					6090	6080	6070				
	10	88	6020	6030	6070											
A06B	14	134	5190	5230	5210											
A08B	16		5340	5280	5350											
	17		5290	5380	5280											
A09B	18		4610	4640	4640											
A11B	19		4790	4790	4720											
A12B	20		4720	5880	4880	5060	4950									
A10B	21		5620	5570	5530											
	22		4400	4840	4810	4760	4710									
A14B	23		5350	5420	5360					5430	5450	5420				
	24		5700	5720	5700	6010				5390	6010	6100	5840			
A15B	25		3970	3980	4010					4330	4330	4330				

Feature	Core Hole	FWD Drop Number	PSPA 1 Modulus (ksi)							PSPA 2 Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
T10A	26		4370	4390	4370	4380	4380	4370								
	28		4490	4480	4990											
	29	265	5160	5230	5120	5760	5660	5690								
	99		3350	3420	3450					4710	4740	4710				
A25B	27		4450	4460	4570											
T09A	30		6310	6290	6300											
	31		4620	4590	4600											
A20B	32	279	4660	4680	4650											
	33	284	4290	4290	4350											
A15B	34	300	4280	4280	4260											
A17B	35	309	5230	4880	4750	5370										
	37	322	4460	4460	4430											
A16B	36	315	5070	4760	5110											
	38	335	4910	4930	4890											
A29B	39	340	3840	3720	3670	4820	5570	5510	5470							
	40		6080	6080	6090											
A21B	44	378	4580	4520	4660											
T07C	45		5030	5220	5190											
	47	395	5080	6440	5460	5460										
T06C	46		834	816	819											
T08C	48		508	511	514											
A23B	49	415	3490	4010	4010	4090										
	50	410	4640	4660	4700											

Feature	Core Hole	FWD Drop Number	PSPA 1 Modulus (ksi)							PSPA 2 Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
T11C	51		463	463	463											
T14C	52		516	507	504											
T15C	53		4680	5250	5260	5440	6920	6760	6830							
T16C	54		504	504	513					597	607	613				
	55		450	447	456					1252	1270	969				
A26B	56	507	6310	6320	5880	6200	5990	6470		5590	4940	5530				
A28B	57	517	5220	5910	5870					4530	4480	4910				
	58		5460	6190	6240					5390	5420	5440				
	59	519	5390	4930	5500	5450				5130	5150	5200				
A27B	60	547	3940	4000	3980					5730	5550	5560				
	61	551	4680	4660	4660					5840	5210	5260				
	62	557	3890	3930	3930					5550	5580	5350				
A24B	63	440	4530	4540	4570					5930	5870	5910				
T13C	64		576	590	590					533	529	556				
	65		613	620	633					677	684	694				
T17C	66	571	5750	5760	5770					5250	5740	5720	4820			
T12A	67		615	619	625					565	561	578				
T03C	68	113	4840	4870	4910											
	69	109	6050	6080	5950											
R01A	71		776	776	779					1061	1058	1053				
	73		794	814	809					909	914	932				
002C	72		532	517	520					488	479	479				

Feature	Core Hole	FWD Drop Number	PSPA 1							PSPA 2						
			Modulus (ksi)							Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
R02A	74	621	5110	5300	5480					5720	5040	5030				
	75	635	4990	5170	5030					5360	5360	5360				
	76	641	5880	5900	6010					5260	5790	5240				
	77	636	5200	5170	5200					6060	5980	6020	5950	5170		
R04C	78	651	4680	4760	4670					5380	6090	6070				
	81	660	5030	5020	5000					4830	4960	5320				
	83		4760	4780	4800					5080	5150	5200				
	86		6040	5130	5110					5910	5910	6020				
R04C	88	730	5170	5230	5260					5640	5590	5520				
	89		5320	5270	5240					6220	6230	6230				
R03C	79		5010	5060	5090					4950	4870	4610				
	80	653	4350	4410	4460					4920	5240	4990				
	82	681	4440	4450	4460					4810	5080	5140	5130			
	84	862	4720	4760	4740					5670	5710	5680				
	85	683	4640	4680	4650					5930	5920	5960				
	87		4290	4950	4940					6230	6250	6260				
	90	685	5710	5790	5820					5890	5940	5890	5880			
R11A	91		6820	6800	6790					6840	6860	6900				
R12A	92	743	5900	5920	5940					5390	5900	5940				
T18C	95		6620	6650	6630					5560	5600	5600				
	96	770	4570	4500	4540					5120	5070	5090	4900			
T19C	97	805	5540	5590	5560					5360	5350	5350				
T05C	98	791	5130	5150	5150					5620	5610	5670				

Appendix B: Raw Data, Barksdale Air Force Base (BAFB)

Table B1. PCC pavements core hole raw data, BAFB.

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
T05A	1		5220	5200					
T08A	2		6500	6690					
	9		7400	7480	7550				
T06A	3	26	6460	6340					
A02B	4	65	7280	5190	5060	7690	5870		
A03B	5	16	5690	5700	5480				
A04B	6	104	5320	4750	5250				
A05B	7	76	5240	5720					
T07A	8		4860	4920					
A49B	10		4620	4690					
A48B	11	229	5780	5800					
A43B	12	254	5760	5700					
A57B	13	274	6030	6100					
	14	285	5980	6010					
A58B	15	318	5920	5920	5920				
A67B	16	304	5560	5620					
A56B	17	334	5990	5990	5380	5370			
A61B	18	376	5300	5280					
A41B	19		5420	5420	7110	7100			
A62B	20	353	5840	5620	5510	5120	5030		
	21		5800	5820	5790	5800	4950	4760	5030
A55B	22	420	4360	4340					
A31B	23	441	5020	4980	4980				
A54B	24	472	5170	5310					
A50B	25		5420	5420					
T30A	26		6420	6490	6440	6340	6240		
T17A	27		5790	5990	6020				
T29A	28		6860	5680	5970	5910	5930		
A45B	29		5410	5250	5150	5420	5740	5160	5170
T27A	30		6360	5490					
A38B	31		5940	5980	6070				
T28A	32		5520	5470	5530				
R15A	33		6390	6250					

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)						
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
R14A	34	549	4440	4450					
R13A	35	564	5500	5410					
R18C	36	579	3920	3940					
	38	619	4580	4630					
R07A	40	729	5660	5870					
T04C	41		4020	3940	3660	3650			
A51B	42	460	6990	6420					
A10B	43	904	6580	6540					
T13C	44	935	5880	5150					
T14C	45	917	6870	6830					
A17B	46		6120	6180					
A19B	47		5020	5160					
A21B	48		4160	4160					
A63B	49	1157	5120	5120					

Table B2. AC pavements raw data, BAFB.

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
R17C	37	610	4320	4410	4330
R10C	39	635	3840	3880	3960

NOTE: These pavements were evaluated as PCC because they had 0.5 in. and 1.5 in., respectively, of AC overlays over two layers of PCC.

Table B3. FWD raw data, BAFB.

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
T05A		1	4930	5490	
		2	5550	5560	
		4	5960	6010	5980
		6	4260	4250	
		8	4330	4380	
		10	5900	6000	
		12	6060	5970	
		14	6280	6420	
T06A		16	3830	3810	
		18	6080	6130	
		20	5690	5720	
		22	5190	5280	
		24	6470	6530	
		26	5380	5430	
		27	5030	4920	
		28	5490	5510	
T08A		29	5450	6520	
		30	5880	5950	
		32	5980	6090	
		34	5330	5930	
		36	5840	5890	
		38	5300	5370	
		39	5670	5750	
		42	5840	5830	
		46	4600	4640	
T39A		47	4940	5120	
		50	5320	5320	
		55	5790	5840	
A02B		60	5040	4980	
	4	65	6430	6540	
A05B		70	5040	4980	
		72	6120	6400	
		74	5850	5910	
	7	76	4910	4890	
		80	5660	5640	
		85	5510		

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A03B		86	7040	7080	
		88	6340	6710	
		90	6120	7200	
		92	6140	6180	
		95	5000	5060	
A04B		100	4200	4700	
	6	104	6030	6110	
		106	7170	7110	
A06B		110	6060	6130	
		112	6870	6820	
		115	5700	5570	
		117	5110	4950	
		120	6070	5810	
		121	5960	6120	
		125	5870	5860	
T10A		130	5610	5470	
		132	5840	5710	
	61	135	5830	5820	
		140	5620	5590	
T09A		145	4960	4950	
		146	6480	6740	
		147	5980	6030	
		150	5790	6410	
		151	5490	5310	
		152	6140	6180	
A07B		155	4400	5940	
		156	7620	6790	
		158	4930	4800	
		160	4190	6640	
		161	6630	6630	
		163	7010	7130	
		165	5980	5220	
		167	4700	4690	
A08B		169	5760	5240	5270
		170	7170	7220	
		172	5120	5110	
		175	6050	5670	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A52B	62	179	5650	5640	
		182	5290	5170	
		184	5440	5450	
		186	5500	5420	
		190	4280	4350	4340
		192	6840	7890	
		195	5150	5080	
T07A		201	6050	5400	6050
	8	205	5900	5360	5350
		207	6570	6600	
		210	6990	6420	
		213	6310	6310	
A49B		222	6150	6140	
		224	6350	6400	6280
		226	5770	5790	5790
		228	5720	5770	
	11	229	6570	6600	6650
		230	6880	6870	
		232	7030	6210	
		234	6630	6560	6390
		236	7160	7120	
		238	5780	5800	
		240	6690	6730	
		242	4960	4900	
		244	6660	5830	
		246	5310	5380	
		248	6490	6280	
		250	5400	5650	
		252	4780	4760	
A43B	12	254	5350	5360	
		256	5160	5210	
		260	5050	5190	
		263	5490	5440	
		264	4470	4470	
		266	4660	4990	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A57B		268	5590	6140	
		270	6230	6830	
		272	5660	5970	
	13 (274)	275	5950	6190	
		277	6480	6520	
		280	6030	5960	
		284	5550	5540	
	14 (285)	287	6090	5890	5750
		290	5630	5570	5530
		293	4850	4920	
A67B		296	5190	4990	5010
		298	5200	5190	
		300	4600	4660	
		302	4990	4970	
	16	304	6350	6190	6170
		306	6160		
		308	5850	5830	
		310	6060	6070	
A58B		312	6640	6510	6110
		315	5560	5570	
		317	5400	5590	
		320	5480	5600	5420
		322	6010	5910	
		324	4910	4970	
		326	6090	5690	
		328	5520	5590	
		330	5730	5800	
A56B		331	5280	5260	
	17	334	5520	5510	
		337	5400	5400	
		340	5020	5590	
		343	5190	5080	
		345	5470	5220	
A62B		346	5660	5720	
		347	5510	5380	
		351	5740	5890	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A62B	20	353	5010	5520	
		355	5620	5590	
		360	5600	5550	
		365	4780	4770	
		370	5190	5270	
A61B		372	5560	6180	
		375	5010	5010	
	18	376	5410	5420	
		380	4850	4840	
		385	5110	5690	
A41B		386	5750	5140	
		390	6440	6380	
		395	5190	5200	
		396	5700	5710	
		400	5530	5600	
A55B		404	4790	4750	
		406	5280	5580	
		410	5520	5560	
		415	5540	6070	
	22	420	5560	5660	5710
		425	5300	5290	
		430	5210	5210	
A31B		434	4750	4740	
		437	5950	5990	
		440	5700	5760	
	23	441	5690		
		445	5570	5550	
A51B		450	6840	6780	
		455	6640	6690	
	42	460	6160	6170	
		463	5780		
		465	6440	6460	
A54B		467	6380	6420	
		470	3700	4860	
	24	472	5510	5660	
		475	4790	4590	
R14C		557	6100	6120	
		558	5990	6070	
		560	6140	6150	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
R13C		561	6390	6390	
		563	7870	8010	
	35	564	5840	5850	
		566	6160	6730	
		568	6110	6170	
		570	5600	5920	
		572	5670	5640	
R18C		573	4250	4300	
		575	4320	4320	
		577	5020	4990	
	36	579	5170	5000	
		581	5670	5690	
		583	5050	5580	
		585	5660	5770	
		588	4810	4720	
		591	5040	5120	
		595	4490	4540	
R17C		598	6280	5720	
		602	5470	5530	
		605	5000	5060	
	37 (610)	611	5400	5400	
		615	6820	5690	
R10C		620	4270	4300	
		625	3320	3390	
		630	4090	4100	
	39	635	3590	3600	
		640	1310	1290	
		645	3930	4020	
		650	3730	3760	
R12C		653	4550	4730	
		655	5270	4770	
		657	5080	5030	
		660	5730	5710	
		663	6030	6080	
R12C		667	4510	4530	
R19C		669	598	592	
		671	421	421	
		675	421	415	
		680	600	600	
		685	498	531	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
R11C		689	3590	3690	
		691	11620	5390	
		695	3420	3300	
		700	3440	3520	
R09C		706	1387	1506	
		710	423	114	
		715	125	125	
		720	758	729	
		725	577	572	
R07A		726	4700	4690	
	40 (729)	739	5560	5540	
		735	4730	4770	
		740	3490	3850	
R04A		745	5650	5820	
		750	6300	5530	
		755	5610	6260	
		759	6070	6050	
R06A		761	5700	4700	
		765	5350	5340	
		770	4680	4200	
R05A		771	6040	6120	
		775	5280	5150	
T04C		780	3810	3800	
		785	3800	3760	
A10B		904	4550	4630	6180
		906	6850	6780	
		907	6680	6720	
		908	6820	6900	
		910	5180	5220	
		912	5660	5600	
A10B		914	6790	6570	
		916	6490	6230	
T14C	45	917	4640	4740	4750
		918	8490	8520	
		920	6340	6370	
		922	5910	5880	
		924	5810	5830	
		926	5370	5460	
		928	6550	6490	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
T13C		930	6670	6650	
		932	5960	5950	
		934	5960	5950	
	44	935	6510	6320	
		936	6710	6730	
		938	7500	7590	
		940	6250	6280	
		942	6270	6300	
		954	4830	4410	
		955	4920	4340	
		956	4910	5000	
		958	6910	6310	5450
		960	5400	5320	
		962	4990	5040	
T17C		964	5880	5130	
		966	5380	5350	
		968	5270	5840	
		971	4650	5040	
		972	5190	5200	
		974	5690	5700	
		975	5230	5280	
A45B		976	5640	5640	5660
		978	4840	4750	
		980	4710	4800	
		982	5670	5630	
		984	3580	3570	
A38B		986	6920	6980	
		988	5520	5580	
		990	5650	5670	
		992	5240	5230	
		994	5360	5310	
		996	5360	5420	
		998	5280	5220	
		1000	5300	5200	
		1002	5230	5320	
		1004	6180	6280	
		1006	6120	6100	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A30B		1008	5650	5730	
		1008	5280	4770	
		1010	5840	5780	
		1012	6640	6650	
A64B		1016	6240	6260	
		1018	5550	5510	
		1020	5610	5650	
		1022	6600	6620	
		1024	6590	6770	
		1026	6480	6510	
		1028	5570	6290	
		1032	7030	6290	
		1033	6160	6180	6200
		1034	5650	5640	
		1036	5640	6170	
		1038	6020	5450	
		1040	6310	6340	
		1042	6300	6300	
		1044	6820	6880	
		1046	6750	6820	
		1048	6300	6330	
A29B		1050	5660	5660	
		1052	5950	5730	
		1054	4900	4330	

Feature	Core Hole	FWD Drop Number	PSPA Modulus (ksi)		
			Test 1	Test 2	Test 3
A25B		1062	4850	4940	
		1064	4950	4900	
		1066	5590	5580	
		1068	5470	5460	
		1070	4830	4850	
		1072	6560	6740	
		1074	6000	6010	
		1076	5810	5180	
		1078	6080	6230	
		1080	5280	5450	
		1082	5950	6060	
		1084	4780	4820	
		1086	5870	5900	
		1088	5460	5320	
		1090	4790	4940	
		1092	5720	5760	
		1094	5050	4610	
		1096	6220	6230	
A17B		1098	5250	5330	
		1100	5970	6050	
		1102	6300	5480	
		1104	5720	5750	
		1106	5780	5180	
		1108	5490	5140	
		1110	6530	6560	
A19B		1111	6290		
		1112	5220	5270	
		1114	6820	6880	
		1116	4650	4800	
		1119	6270	6370	
		1120	7140	7090	
		1122	4920	4890	
		1124	6580	5790	
		1126	4710	4250	
		1128	4500	5150	

Table B4. FFRC raw data, BAFB.

Feature	Core Hole	Length (in.)	Diameter (in.)	Frequency	FFRC Modulus (ksi)
T05A	1 bottom	11.34	5.75	7647	6758
	1 top	11.34	5.75	7378	6291
T08A	2 bottom	8.00	5.75	10893	6824
	2 top	10.00	5.75	8793	6947
	9 bottom	8.25	5.75	10504	6748
	9 top	9.88	5.75	9137	7322
T06A	3 top	11.44	5.75	7070	5879
A02B	4 bottom	11.40	5.75	7587	6721
	4 top	11.40	5.75	7463	6505
A03B	5 bottom	11.40	5.75	7443	6469
	5 top	11.40	5.75	7216	6082
A04B	6 bottom	10.00	5.75	8933	7171
	6 top	8.50	5.75	10483	7135
A05B	7 bottom	11.44	5.75	7767	7095
	7 top	11.44	5.75	7009	5777
T07A	8 bottom	11.40	5.75	7566	6685
	8 top	11.40	5.75	7258	6151
A49B	10	18.75	5.75	4461	6287
A48B	11	17.00	5.75	5114	6791
A43B	12 bottom	12.00	5.75	7480	7241
	12 top	8.13	5.75	10572	6639
A57B	13	21.00	5.75	3996	6327
	14	11.40	5.75	7545	6649
A58B	15	11.37	5.75	7582	6678
A67B	16	11.44	5.75	7542	6689
	16 top	10.13	5.75	8424	6543
A56B	17	11.44	5.75	7665	6909
A61B	18	11.44	5.75	7501	6617
A41B	19	11.44	5.75	7644	6872
A62B	20	11.44	5.75	7316	6295
	21	11.44	5.75	7337	6331
A55B	22	11.44	5.75	7337	6331
A31B	23	11.44	5.75	7275	6225
A54B	24	11.00	5.75	7817	6644
	24 top	7.44	5.75	11656	6758
A50B	25	11.44	5.75	7378	6402
T30A	26 bottom	11.40	5.75	7628	6794
	26 top	11.40	5.75	7484	6541

Feature	Core Hole	Length (in.)	Diameter (in.)	Frequency	FFRC Modulus (ksi)
T17A	27 bottom	11.40	5.75	7648	6831
	27 top	8.25	5.75	10703	7006
T29A	28 bottom	11.44	5.75	7152	6016
	28 top	11.40	5.75	7175	6013
A45B	29 bottom	11.40	5.75	7833	7166
	29 top	11.44	5.75	7665	6909
T27A	30 bottom	11.40	5.75	7422	6433
	30 top	11.44	5.75	7132	5982
A38B	31	11.44	5.75	6107	4386
T28A	32 bottom	11.40	5.75	7504	6576
	32 top	11.40	5.75	7278	6186
R15A	33 bottom	9.25	5.75	8208	5179
	33 top	11.40	5.75	7443	6469
R14A	34	11.30	5.75	7630	6680
R13A	35	11.30	5.75	7360	6216
R18C	36	11.34	5.75	6882	5474
R17C	37 bottom	11.40	5.75	7792	7091
	37 top	8.00	5.75	9810	5534
R18C	38 bottom	11.40	5.75	6682	5214
	38 top	11.13	5.75	6188	4262
R10C	39 bottom	10.0	5.75	8606	6654
	39 top	8.25	5.75	8318	4232
R07A	40 bottom	10.63	5.75	7980	6466
	40 top	9.44	5.75	8959	6427
T04C	41	11.4	5.75	6127	4384
A51B	42	20.50	5.75	4369	7206
A10B	43	11.00	5.75	7838	6680
T13C	44	12.00	5.75	7402	7090
A17B	46	19.00	5.75	4540	6687
A19B	47 bottom	11.38	5.75	7788	7058
	47 top	7.81	5.75	11281	6975
A21B	48 bottom	11.13	5.75	7640	6498
	48 top	8.38	5.75	10549	7022
A63B	49	17.75	5.75	4741	6364

Table B5. PSPAs raw data, BAFB.

Feature	Core Hole	FWD Drop Number	PSPA 1 Modulus (ksi)					PSPA 2 Modulus (ksi)		
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 1	Test 2	Test 3
T05A	1		5220	5200						
T08A	2		6500	6690						
	9		7400	7480	7550					
T06A	3	26	6460	6340						
A02B	4	65	7280	5190	5060	7690	5870			
A03B	5	16	5690	5700	5480					
A04B	6	104	5320	4750	5250					
A05B	7	76	5240	5720						
T07A	8		4860	4920						
A49B	10		4620	4690						
A48B	11	229	5780	5800				6570	6600	6650
A43B	12	254	5760	5700				5350	5360	
A57B	13	274	6030	6100				5950	6190	
	14	285	5980	6010				6090	5890	5750
A58B	15	318	5920	5920	5920					
A43B	16	304	5560	5620				6350	6190	6170
A56B	17	334	5990	5990	5380	5370		5520	5510	
A61B	18	376	5300	5280				5410	5420	
A41B	19		5420	5420	7110	7100				
A62B	20	353	5840	5620	5510	5120	5030	5010	5520	
	21		5800	5820	5790	5800	4950			
A55B	22	420	4360	4340				5560	5660	5710
A31B	23	441	5020	4980	4980			5690		
A54B	24	472	5170	5310				5510	5660	
A50B	25		5420	5420						
T30A	26		6420	6490	6440	6340	6240			
T17A	27		5790	5990	6020					
T29A	28		6860	5680	5970	5910	5930			
A45B	29		5410	5250	5150	5420	5740			
T27A	30		6360	5490						
A38B	31		5940	5980	6070					
	32		5520	5470	5530					
R15A	33		6390	6250						
R14C	34	549	4440	4450						
R13C	35	564	5500	5410				5840	5850	
R18C	36	579	3920	3940				5170	5000	
	38	619	4580	4630						

Feature	Core Hole	FWD Drop Number	PSPA 1 Modulus (ksi)					PSPA 2 Modulus (ksi)		
			Test 1	Test 2	Test 3	Test 4	Test 5	Test 1	Test 2	Test 3
R17C	37	610	4320	4410	4330			5400	5400	
R10C	39	635	3840	3880	3960			3590	3600	
R07A	40	729	5660	5870				5560	5540	
T04C	41		4020	3940	3660	3650				
A51B	42	460	6990	6420				6160	6170	
A10B	43	904	6580	6540						
T13C	44	935	5880	5150				6510	6320	
T14C	45	917	6870	6830				4640	4740	4750
A17B	46		6120	6180						
A21B	47		5020	5160						
A25B	48		4160	4160						
A63B	49	1157	5120	5120						

Appendix C: Raw Data, Phillips Army Airfield (PAAF)

Table C1. PCC pavements raw data, PAAF.

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
A5B	1	4220	4310
	2	5000	5040
	3	3700	4000
	4	4190	4250
	5	4190	4190
A6B	1	4070	4090
	2	4000	4010
	3	3960	3960
	4	3570	3470
	5	3700	3710
A7B	1	4030	4110
	2	3700	3870
	3	4210	4370
	4	4960	4770

Table C2. AC pavements raw data, PAAF.

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
R1A	0	563	563
	1	778	784
	2	554	554
	3	658	646
	4	640	640
	5	643	637
	6	769	787
	7	701	686
	8	686	683
	9	723	717
R2C	10	658	652
	11	665	674
	12	686	677
	13	496	505
	14	631	631
	15	637	631
	16	692	698
	17	778	763
	18	732	710
	19	729	701
	20	717	726
R3C	21	683	683
	22	802	812
	23	591	606
	24	705	720
	25	696	705
	26	720	723
	27	614	611
R4C	28	727	772
	29	269	275
	30	156	159
	31	636	627
	32	595	598
	33	160	163
R4C	34	600	615
	35	572	180

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
R5C	36	633	662
	37	225	219
	38	461	464
	39	724	722
	40	630	630
	41	290	284
R6C	42	617	632
	43	606	642
	44	452	458
	45	183	186
	46	536	139
	47	415	355
	48	173	173
	49	192	195
R7C	50	318	315
	51	384	381
	52	478	459
	53	352	352
	54	499	356
	55	381	381
	56	279	282
	57	452	452
	58	384	372
	59	180	180
	60	316	319
	61	316	316
	62	483	493
	63	299	293
	64	405	408
	65	186	189
	66	340	340
	67	553	532
R7C	68	602	605
	69	612	615
	70	626	629

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
R8A	71	423	423
	72	787	784
	73	440	446
	74	679	685
	75	533	539
	76	705	773
	77	564	561
	78	583	586
	79	604	604
	80	589	583
R9A	0	666	652
	1	591	610
	2	206	209
	3	388	508
R10A	4	209	226
	5	364	367
	6	186	183
R11A	7	619	635
	8	838	826
R12C	9	206	216
	10	186	186
	11	191	185
	12	189	192
	13	221	212
	14	415	415
	15	224	242
	16	320	320
	17	278	275
	18	423	415
	19	333	336
	20	289	280
	21	296	299
	22	417	420
	23	360	357
	24	269	277
	25	447	437
	26	312	323
	27	470	470
	29	402	390

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
R12C	30	330	330
	31	414	423
	32	363	363
	33	624	633
	34	923	915
	35	716	713
	36	709	760
	37	319	322
	38	346	346
	39	260	263
R13A	40	266	272
	41	291	285
	42	243	246
	43	294	297
	44	329	329
	45	735	759
	46	289	286
	47	314	314
R14A	48	497	497
	49	448	456
	50	607	543
R15A	0	588	602
	1	586	621
R16A	2	442	475
	3	293	290
	4	392	398
	5	341	359
	6	338	316
R16A	7	595	607
	8	468	440
	9	392	404

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
R17C	10	223	237
	11	290	306
	12	237	240
	13	641	808
	14	707	687
	15	175	175
	16	538	535
	17	362	362
	18	436	426
	19	147	150
	20	176	166
	21	175	165
	22	196	176
	23	184	184
	24	511	531
	25	302	299
	26	305	200
	27	196	196
	28	325	328
	29	1057	705
	30	443	477
	31	471	471
	32	247	237
	33	193	190
	34	738	724
	35	192	204
	36	247	244
	37	211	198
	38	524	528
R18A	39	240	233
	40	262	269
	41	233	224
R18A	42	213	203
	43	284	272
	44	1543	1500
	45	145	145
R19A	46	756	733
	47	312	319
	48	453	469

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
T1A	0	1019	1059
	1	886	853
	2	418	421
	3	514	524
	4	441	431
	5	790	801
	6	730	710
	7	312	309
	8	206	209
	9	362	378
	10	226	226
	11	358	345
	12	441	455
T2A	13	544	518
	14	559	569
	15	315	315
	16	569	572
	17	382	392
	18	231	241
	19	265	269
	20	237	235
	21	189	189
	22	602	576
	23	511	514
	24	305	305
	25	246	246
	26	301	291
	27	475	472
T2A	28	210	217
	29	190	187

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
T3A	30	226	220
	31	538	554
	32	375	391
	33	338	345
	34	495	498
	35	448	441
	36	414	411
	37	365	362
	38	511	504
	39	300	310
	40	450	443
	41	270	264
	42	327	327
	43	699	702
	44	408	411
	45	429	429
	46	605	598
	47	398	401
	48	501	504
	49	410	410
	50	391	397
T4B	0	201	201
	1	391	391
	2	373	359
	3	426	444
	4	461	451
	5	495	508
	6	363	359
	7	771	771
	8	553	599
	9	588	556
T5B	0	870	848
	1	692	730
	2	723	711
T5B	3	514	474
	4	595	583
	5	561	636
	6	268	277

Feature	Station	PSPA Modulus (ksi)	
		Test 1	Test 2
A3B	1	496	597
	2	500	507
	3	529	525
	4	438	442
	5	601	579
	6	163	174
	7	757	369
A4B	1	314	210
	2	489	448
	3	276	305

Appendix D: 1996 Pavement Technical Assistance Program (PTAP) Data and 2005 Innovative Pavement Research Foundation (IPRF) Data

Table D1. 1996 PTAP data.

Aggregate	Mix Strength	Age (day)	PSPA Modulus (ksi)	Flex Strength (psi)
Cr Limestone (Low)	1L	1.50	4258	366
Cr Limestone (Low)	1L	6.91	4904	483
Cr Limestone (Low)	1L	13.94	5373	550
Cr Limestone (Low)	1L		5920	601
Cr Limestone (High)	1H	1.54	5953	629
Cr Limestone (High)	1H	6.89	6456	663
Cr Limestone (High)	1H	13.90	6522	789
Cr Limestone (High)	1H		6610	824
River Gravel (Low)	2L	1.36	3610	325
River Gravel (Low)	2L	6.99	4304	426
River Gravel (Low)	2L	13.96	4602	458
River Gravel (Low)	2L	27.95	5220	474
River Gravel (High)	2H	1.49	4453	540
River Gravel (High)	2H	6.89	4582	578
River Gravel (High)	2H	13.91	4853	598
River Gravel (High)	2H	27.88	5115	594

Table D2. 2005 IPRF data.

Aggregate	Mix Design	Age (day)	PSPA Modulus (ksi)	Flex Strength (psi)
Granite	Standard	1	3926	
Granite	Standard	3	4095	693
Granite	Standard	7	5247	645
Granite	Standard	14	5231	632
Granite	Standard	28	5221	692
Granite	Low WCR	1	4868	
Granite	Low WCR	3	6211	691
Granite	Low WCR	7	5363	703
Granite	Low WCR	14	5590	684
Granite	Low WCR	28	5847	777
Granite	High WCR	1	4331	
Granite	High WCR	3	5292	570
Granite	High WCR	7	5082	623
Granite	High WCR	14	5551	707
Granite	High WCR	28	5042	735
Granite	More Cement	1	4496	
Granite	More Cement	3	4835	592
Granite	More Cement	7	5152	602
Granite	More Cement	14	5613	627
Granite	More Cement	28	5758	673
Granite	Less Cement	1	4822	
Granite	Less Cement	3	4535	547
Granite	Less Cement	7	4842	612
Granite	Less Cement	14	4690	633
Granite	Less Cement	28	4815	707
Granite	High CAF	1	4528	
Granite	High CAF	3	4765	635
Granite	High CAF	7	5203	684
Granite	High CAF	14	5781	708
Granite	High CAF	28	5896	742
Granite	Low CAF	1	4153	
Granite	Low CAF	3	4859	590
Granite	Low CAF	7	5538	603
Granite	Low CAF	14	5000	608
Granite	Low CAF	28	5954	625
Granite	Blanket (Std)	1	4953	
Granite	Blanket (Std)	3	5467	619
Granite	Blanket (Std)	7	5944	627

Aggregate	Mix Design	Age (day)	PSPA Modulus (ksi)	Flex Strength (psi)
Granite	Blanket (Std)	14	5768	645
Granite	Blanket (Std)	28	5993	648
Granite	Untreated (Std)	1	4095	
Granite	Untreated (Std)	3		
Granite	Untreated (Std)	7	5306	536
Granite	Untreated (Std)	14	5341	580
Granite	Untreated (Std)	28	5968	663
Granite	FAA Std	1	5126	
Granite	FAA Std	3	4975	627
Granite	FAA Std	7	4701	627
Granite	FAA Std	14	4672	585
Granite	FAA Std	28	5046	640
SRG	Std	1	3327	
SRG	Std	3	3551	465
SRG	Std	7	3718	496
SRG	Std	14	3676	
SRG	Std	28	3372	452
SRG	Low WCR	1	3650	
SRG	Low WCR	3	4257	565
SRG	Low WCR	7	4269	620
SRG	Low WCR	14	4157	
SRG	Low WCR	28	4108	588
SRG	High WCR	1	3097	
SRG	High WCR	3	3211	466
SRG	High WCR	7	3239	504
SRG	High WCR	14	3249	
SRG	High WCR	28	3292	444
SRG	18" Slab	1	3008	
SRG	18" Slab	3	3251	466
SRG	18" Slab	7	3223	484
SRG	18" Slab	14	3652	
SRG	18" Slab	28	3341	534
SRG	6" Slab	1	3235	
SRG	6" Slab	3	3502	516
SRG	6" Slab	7	3562	446
SRG	6" Slab	14	3441	
SRG	6" Slab	28	3596	449
SRG	12" Over compacted	1	2894	
SRG	12" Over compacted	3	3024	464

Aggregate	Mix Design	Age (day)	PSPA Modulus (ksi)	Flex Strength (psi)
SRG	12" Over compacted	7	2846	448
SRG	12" Over compacted	14	3367	
SRG	12" Over compacted	28	3435	476
SRG	Untreated Slab	1	3189	
SRG	Untreated Slab	3	3854	445
SRG	Untreated Slab	7	3869	424
SRG	Untreated Slab	14	3991	
SRG	Untreated Slab	28	4080	442
SRG	Blanketed Slab	1	3356	
SRG	Blanketed Slab	3	3904	465
SRG	Blanketed Slab	7	4032	470
SRG	Blanketed Slab	14	4220	
SRG	Blanketed Slab	28	4335	485
SRG	Humidity Low	1	3426	
SRG	Humidity Low	3	3582	502
SRG	Humidity Low	7	3963	435
SRG	Humidity Low	14	4325	
SRG	Humidity Low	28	4476	465
SRG	Humidity High	1	3835	
SRG	Humidity High	3	4027	460
SRG	Humidity High	7	4116	532
SRG	Humidity High	14	4533	
SRG	Humidity High	28	4699	659
SRG	High Temp Cure	1	3543	
SRG	High Temp Cure	3	3778	453
SRG	High Temp Cure	7	3838	518
SRG	High Temp Cure	14	4036	
SRG	High Temp Cure	28	4212	430
SRG	Low Temp Cure	1	3432	
SRG	Low Temp Cure	3	3815	407
SRG	Low Temp Cure	7	4076	419
SRG	Low Temp Cure	14	4615	
SRG	Low Temp Cure	28	4456	487

Appendix E: Standard Normal Distribution

Table E1. Table of the standard normal distribution.

Z		0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0		0.0000	0.0040	0.0080	0.0120	0.0160	0.0190	0.0239	0.0279	0.0319	0.0359
0.1		0.0398	0.0438	0.0478	0.0517	0.0557	0.0596	0.0636	0.0675	0.0714	0.0753
0.2		0.0793	0.0832	0.0871	0.0910	0.0948	0.0987	0.1026	0.1064	0.1103	0.1141
0.3		0.1179	0.1217	0.1255	0.1293	0.1331	0.1368	0.1406	0.1443	0.1480	0.1517
0.4		0.1554	0.1591	0.1628	0.1664	0.1700	0.1736	0.1772	0.1808	0.1844	0.1879
0.5		0.1915	0.1950	0.1985	0.2019	0.2054	0.2088	0.2123	0.2157	0.2190	0.2224
0.6		0.2257	0.2291	0.2324	0.2357	0.2389	0.2422	0.2454	0.2486	0.2517	0.2549
0.7		0.2580	0.2611	0.2642	0.2673	0.2704	0.2734	0.2764	0.2794	0.2823	0.2852
0.8		0.2881	0.2910	0.2939	0.2969	0.2995	0.3023	0.3051	0.3078	0.3106	0.3133
0.9		0.3159	0.3186	0.3212	0.3238	0.3264	0.3289	0.3315	0.3340	0.3365	0.3389
1.0		0.3413	0.3438	0.3461	0.3485	0.3508	0.3513	0.3554	0.3577	0.3529	0.3621
1.1		0.3643	0.3665	0.3686	0.3708	0.3729	0.3749	0.3770	0.3790	0.3810	0.3830
1.2		0.3849	0.3869	0.3888	0.3907	0.3925	0.3944	0.3962	0.3980	0.3997	0.4015
1.3		0.4032	0.4049	0.4066	0.4082	0.4099	0.4115	0.4131	0.4147	0.4162	0.4177
1.4		0.4192	0.4207	0.4222	0.4236	0.4251	0.4265	0.4279	0.4292	0.4306	0.4319
1.5		0.4332	0.4345	0.4357	0.4370	0.4382	0.4394	0.4406	0.4418	0.4429	0.4441
1.6		0.4452	0.4463	0.4474	0.4484	0.4495	0.4505	0.4515	0.4525	0.4535	0.4545
1.7		0.4554	0.4564	0.4573	0.4582	0.4591	0.4599	0.4608	0.4616	0.4625	0.4633
1.8		0.4641	0.4649	0.4656	0.4664	0.4671	0.4678	0.4686	0.4693	0.4699	0.4706
1.9		0.4713	0.4719	0.4726	0.4732	0.4738	0.4744	0.4750	0.4756	0.4761	0.4767
2.0		0.4772	0.4778	0.4783	0.4788	0.4793	0.4798	0.4803	0.4808	0.4812	0.4817
2.1		0.4821	0.4826	0.4830	0.4834	0.4838	0.4842	0.4846	0.4850	0.4854	0.4857
2.2		0.4861	0.4864	0.4868	0.4871	0.4875	0.4878	0.4881	0.4884	0.4887	0.4890
2.3		0.4893	0.4896	0.4898	0.4901	0.4904	0.4906	0.4909	0.4911	0.4913	0.4916
2.4		0.4918	0.4920	0.4922	0.4925	0.4927	0.4929	0.4931	0.4932	0.4934	0.4936
2.5		0.4938	0.4940	0.4941	0.4943	0.4945	0.4946	0.4948	0.4949	0.4951	0.4952
2.6		0.4953	0.4955	0.4956	0.4957	0.4959	0.4960	0.4961	0.4962	0.4963	0.4964
2.7		0.4965	0.4966	0.4967	0.4968	0.4969	0.4970	0.4971	0.4972	0.4973	0.4974
2.8		0.4974	0.4975	0.4976	0.4977	0.4977	0.4978	0.4979	0.4979	0.4980	0.4981
2.9		0.4981	0.4982	0.4982	0.4983	0.4984	0.4984	0.4985	0.4985	0.4986	0.4986
3.0		0.4987	0.4987	0.4987	0.4988	0.4988	0.4989	0.4989	0.4989	0.4990	0.4990
3.1		0.4990	0.4991	0.4991	0.4991	0.4992	0.4992	0.4992	0.4992	0.4993	0.4993
3.2		0.4993	0.4993	0.4994	0.4994	0.4994	0.4994	0.4994	0.4995	0.4995	0.4995
3.3		0.4995	0.4995	0.4995	0.4996	0.4996	0.4996	0.4996	0.4996	0.4996	0.4997
3.4		0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4997	0.4998

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14. ABSTRACT
An assessment of the portable seismic pavement analyzer (PSPA) was conducted during the period February to April 2005 on three military airfields in order to determine the feasibility of rapidly obtaining the modulus and flexural strength of portland cement concrete and asphalt concrete pavements. The PSPA is a nondestructive testing device that measures seismic modulus using ultrasonic surface waves. The objective of this research is to evaluate the PSPA as an alternative to core sampling. This would potentially reduce the amount of time required for testing and eliminate the need for laboratory testing of concrete cores. This report provides (a) background information on the PSPA, (b) a summary of recent PSPA research, (c) test methods used in airfield evaluations, (d) field testing information, (e) data analysis, and (f) recommendations for utilizing flexural strength relationships.

15. SUBJECT TERMS

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